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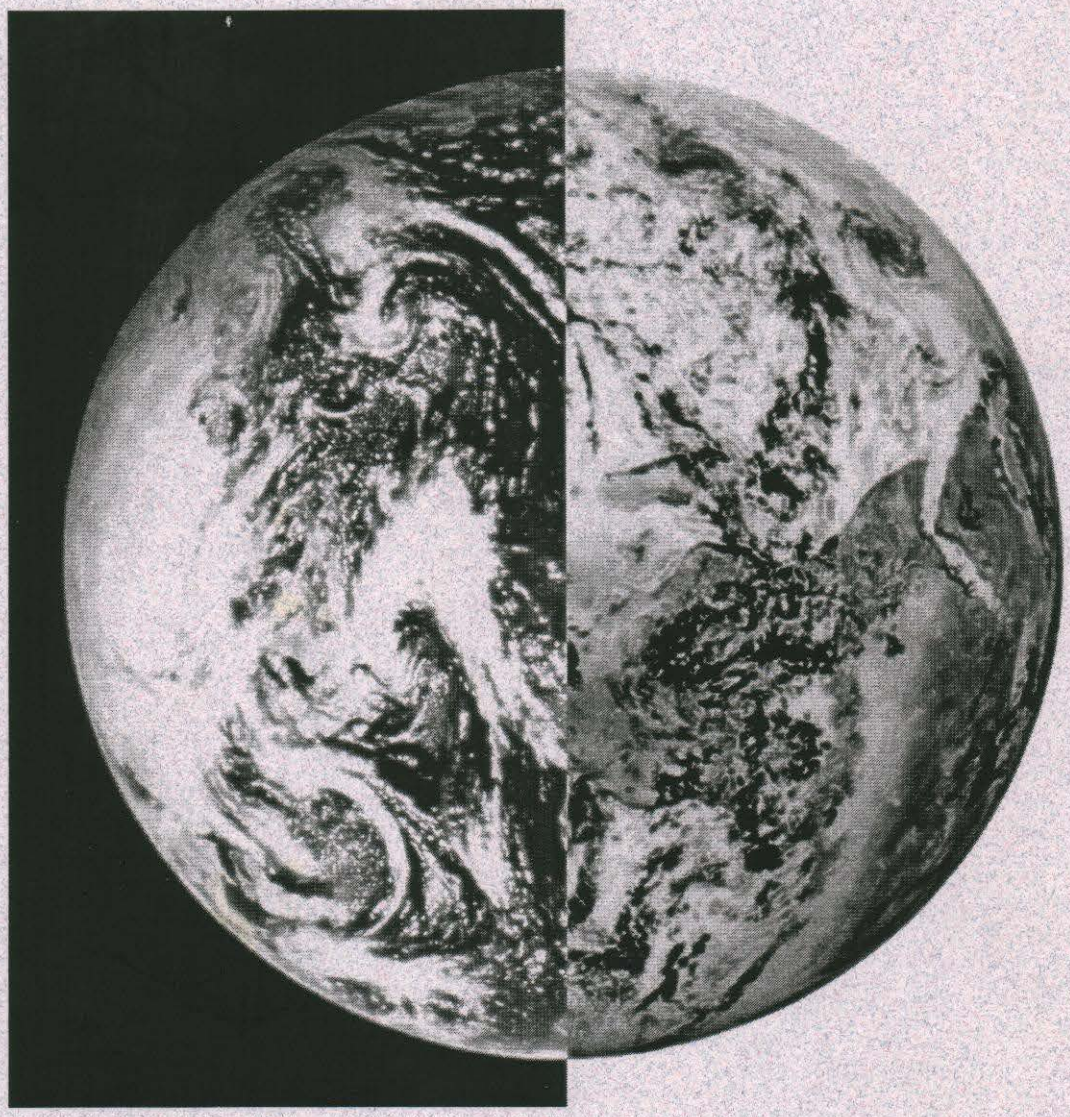
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Climate Change Action Plan

For public consultation and review

October 1997

USAID

U.S. Agency for International Development

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Divider Title: **8**

DOE/EIA-0573(96)
Distribution Category UC-950

Emissions of Greenhouse Gases in the United States 1996

October 1997

Energy Information Administration
Office of Integrated Analysis and Forecasting
U.S. Department of Energy
Washington, DC 20585

This report was prepared by the Energy Information Administration, the independent statistical and analytical agency within the Department of Energy. The information contained herein should not be construed as advocating or reflecting any policy position of the Department of Energy or of any other organization.

Preface

Title XVI, Section 1605(a) of the Energy Policy Act of 1992 (enacted October 24, 1992) provides:

> *Not later than one year after the date of the enactment of this Act, the Secretary, through the Energy Information Administration, shall develop, based on data available to, and obtained by, the Energy Information Administration, an inventory of the national aggregate emissions of each greenhouse gas for each calendar year of the baseline period of 1987 through 1990. The Administrator of the Energy Information Administration shall annually update and analyze such inventory using available data. This subsection does not provide any new data collection authority.*

The first report in this series, *Emissions of Greenhouse Gases 1985-1990*, was published in September 1993. This report—the fifth annual report, as required by law—presents the Energy Information Administration's latest estimates of emissions for carbon dioxide, methane, nitrous oxide, and other greenhouse gases.

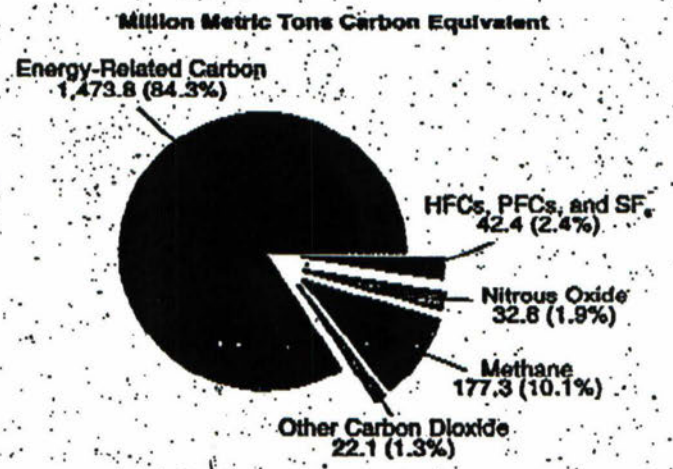
Executive Summary

In 1996, U.S. emissions of greenhouse gases increased by 3.4 percent over 1995 emissions, the highest rate of increase in recent years. Although U.S. emissions have been growing since 1991, their growth accelerated in 1996. Greenhouse gas emissions expanded more rapidly than U.S. energy consumption in 1996, and the growth of energy consumption (up 3.2 percent) exceeded the growth of the U.S. economy (up 2.4 percent).[1] Three principal sources contributed to the growth in U.S. greenhouse gas emissions:

- Energy consumption increased more rapidly in 1996 than in recent years, buoyed by strong economic growth and unusually severe weather. Residential and commercial carbon dioxide emissions (including their prorated share of electric utility emissions) expanded by 6.3 and 5.5 percent, respectively.
- The rapid growth of relatively low-carbon natural gas consumption, which has tended to moderate the growth of total carbon dioxide emissions in recent years by "capping" high-carbon coal use, slowed as natural gas prices increased. Consequently, electric utilities met the demand for increased electricity largely with coal-fired power generation. Electric utility carbon dioxide emissions increased by 4.7 percent, divided between a 2.4-percent rise resulting from increased electricity sales and a 2.3-percent increase resulting from the use of fuels with higher carbon content.
- Estimated emissions of exotic gases, such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride—paced by increased emissions of HFC-134a, the widely accepted substitute for chlorofluorocarbons (CFCs)—grew by more than 10 percent in 1996, though from very low levels.

Table ES1 shows trends in emissions of the principal greenhouse gases, measured in million metric tons of gas. In Table ES2, the value shown for each gas is weighted by its global warming potential (GWP), which is as a measure of radiative forcing. This concept, developed by the Intergovernmental Panel on Climate Change (IPCC),[2] provides a comparative measure of the impacts of different greenhouse gases on global warming, with the effect of carbon dioxide being equal to 1 (see "Units for Measuring Greenhouse Gases" on page 5). The GWPs for other greenhouse gases are considerably higher (see discussion in Chapter 1). Overall, GWP-weighted emissions rose by 8.3 percent between 1990 and 1996 and by 3.4 percent between 1995 and 1996. On a GWP-weighted basis, carbon dioxide emissions account for 85 percent of U.S. greenhouse gas emissions (Figure ES1). While carbon dioxide emissions are growing, methane and nitrous oxide emissions have been roughly stable.

Figure ES1. U.S. Greenhouse Gas Emissions by Gas, 1996



Source: EIA estimates documented in this report.

Table ES2 excludes several radiatively important gases: the criteria pollutants carbon monoxide, nitrogen oxides, and particulates, as well as CFCs and hydrochlorofluorocarbons (HCFCs). These gases have ambiguous effects on climate, which are difficult to quantify. In addition, CFCs and HCFCs are specifically excluded from coverage under the international climate treaty, the Framework Convention on Climate Change. (See Chapters 1, 5, and 6 for discussion related to the effects and emissions of these gases.)

[1] Energy Information Administration, *Annual Energy Review 1996*, DOE/EIA-0384(96) (Washington, DC, July 1997), pp. 5 and 367.
[2] Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996).

The historical emissions estimates for the years 1989 through 1995 presented in this report are only slightly revised from those in last year's report (see the box on page 2, "What's New in This Report").

Table ES1. Estimated U.S. Emissions of Greenhouse Gases by Gas, 1989-1996
(Million Metric Tons of Gas)

Gas	1989	1990	1991	1992	1993	1994	1995	P1996
Carbon Dioxide	5,091.8	5,037.1	4,987.3	5,059.8	5,175.9	5,256.1	5,296.9	5,484.9
Methane	31.3	31.6	31.6	31.7	30.8	31.4	30.9	30.9
Nitrous Oxide	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.4
Halocarbons and Minor Gases								
CFC-11, CFC-12, CFC-113	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.1
HCFC-22	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
HFCs, PFCs, and SF_6	*	*	*	*	*	*	*	*
Methyl Chloroform	0.3	0.3	0.2	0.2	0.1	0.1	*	*
Criteria Pollutants								
Carbon Monoxide	93.5	91.3	88.3	85.3	85.4	89.6	83.5	NA
Nitrogen Oxides	21.1	20.9	20.6	20.7	21.1	21.5	19.7	NA
Nonmethane VOCs	21.7	21.4	20.8	20.3	20.5	21.1	20.7	NA

*Less than 50,000 tons of gas. Estimated hydrofluorocarbon, perfluorocarbon, and sulfur hexafluoride emissions combined totaled 0.008 million metric tons in 1989, rising to 0.034 million metric tons in 1996.

P = preliminary data. NA = not available.

Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1995*, DOE/EIA-0573(95) (Washington, DC, October 1996).

Sources: **Carbon dioxide, methane, nitrous oxide emissions:** EIA estimates described in Chapters 2, 3, and 4 of this report. **Halocarbons and minor gases:** 1990 and 1994 estimates from the U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-1994*, EPA-230-R-96-006 (Washington, DC, November 1995), pp. 46-50. Other years from EIA estimates described in Chapter 5 of this report. **Criteria pollutants:** U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *National Air Pollutant Emission Trends, 1900-1995*, EPA-454/R-96-007 (Research Triangle Park, NC, October 1996), Tables A-1–A-3, pp. A-2–A-16.

Table ES2. U.S. Emissions of Greenhouse Gases, Based on Global Warming Potential, 1989-1996
(Million Metric Tons of Carbon or Carbon Equivalent)

Gas	1989	1990	1991	1992	1993	1994	1995	P1996
Carbon	1,389	1,374	1,360	1,380	1,412	1,433	1,445	1,496
Methane	179	181	181	182	177	180	177	177
Nitrous Oxide	38	38	38	38	39	40	38	38
HFCs, PFCs, and SF_6	26	25	26	28	27	31	36	42
Total	1,632	1,618	1,606	1,628	1,654	1,684	1,696	1,753

P = preliminary data.

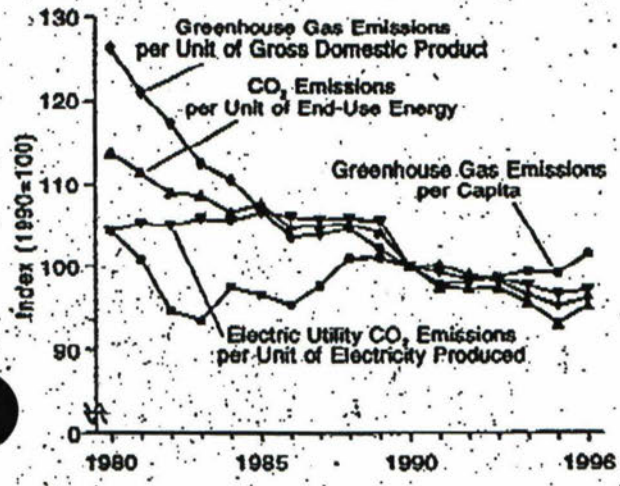
Note: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 1995*, DOE/EIA-0573(95) (Washington, DC, October 1996).

Sources: EIA estimates documented in this report.

Carbon Dioxide

me 98.5 percent of U.S. anthropogenic carbon dioxide emissions come from the combustion of fossil fuels. Changes in carbon dioxide emissions can be traced to energy consumption trends and changes in the composition of fossil fuels burned to provide energy services. During the 1980s and early 1990s, the energy intensity of the U.S. economy and the carbon intensity of U.S. energy consumption steadily declined (Figure ES2).

Figure ES2. Emissions Intensity of U.S. Gross Domestic Product, Population, Energy Use, and Electricity Production, 1980-1996



Sources: EIA estimates documented in this report.

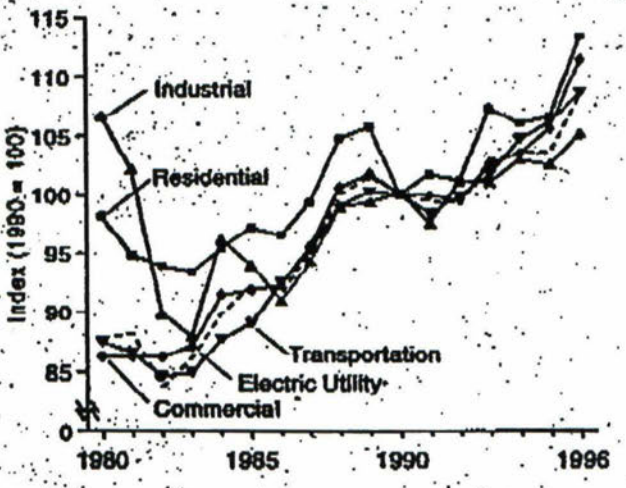
Several unrelated factors caused the decline:

- The deregulation of the natural gas industry bore fruit in the form of greatly increasing gas supplies at low prices. Natural gas use expanded rapidly in the residential, commercial, and industrial sectors, accounting for much of the growth of energy consumption.
- Many events of the period—including the Gulf War, the oil price spike of 1990, the recession of 1991, and the vogue for utility demand-side management programs—tended to restrain the growth of energy consumption.
- Utility operators began to solve nuclear power plant operating problems and, by 1995, were able to produce 17 percent more electricity from nuclear plants than in 1990.
- With more snowfall in the Pacific Northwest, hydroelectric power generation has returned to the levels of the early 1980s. Despite widespread allocation of water to accommodate salmon, 1996 hydroelectric generation was the second highest on record.

Currently, however, the growth in nuclear power generation has leveled off, and it is unlikely that future hydroelectric generation will often match 1996 levels. World oil prices remain relatively low, and the U.S. economy is growing rapidly.

Severe weather conditions in 1996 produced a series of anomalous results: residential and commercial natural gas consumers used 7.8 percent more natural gas and 3.5 percent more electricity than in 1995, and natural gas prices increased sharply. In response to the price signals, electric utilities reduced their gas consumption by 15 percent and substituted coal. The result was a sharp increase in both total carbon emissions and emissions per kilowatthour for the electric utility sector, accompanied by rapid increases in both direct (from natural gas and heating oil) and indirect (from electricity) emissions from the residential and commercial sectors. Emissions from the industrial and transportation sectors increased by a "more normal" 2.6 percent and 2.3 percent, respectively, in 1996 (Figure ES3).

Figure ES3. U.S. Carbon Dioxide Emissions by Sector, 1980-1996



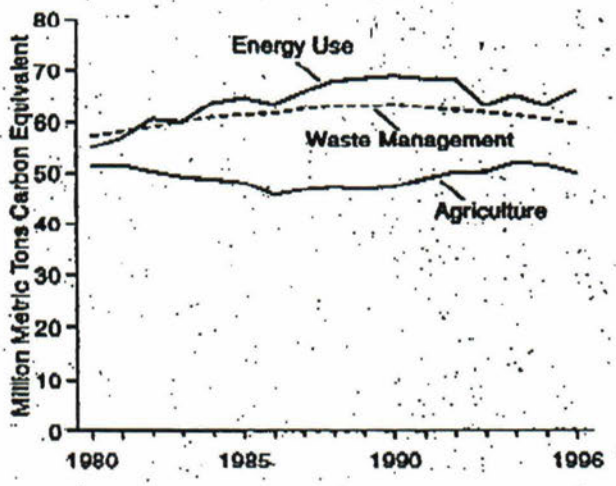
Source: EIA estimates documented in Chapter 2 of this report.

Methane

Methane emissions estimates are more uncertain than those for carbon dioxide. U.S. anthropogenic methane emissions have three principal sources: production and transportation of coal, natural gas, and oil; anaerobic decomposition of municipal waste in landfills; and

raising livestock. Smaller sources include combustion of fossil fuels, rice cultivation, and industrial processes. Estimated 1996 methane emissions are unchanged from emissions in 1995 (Figure ES4).

Figure ES4. U.S. Methane Emissions by Source, 1980-1996



Source: EIA estimates documented in Chapter 3 of this report.

Note: Methane emissions from industrial sources were approximately 750,000 metric tons in 1996.

Methane emissions rose during the late 1980s. The principal cause appears to have been increased production from a group of underground coal mines with very high rates of methane emissions. Meanwhile, emissions from municipal landfills appear to have been stable, because growth in the volume of solid waste generated was offset by a growing volume of waste burned for energy recovery and by increased recovery of methane at landfill sites.

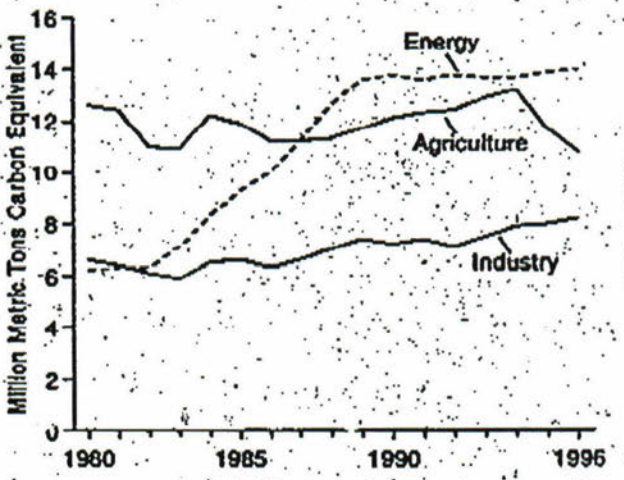
In the 1990s, several factors have tended to limit or reduce estimated methane emissions:

- The rapid expansion of recycling (particularly of paper and garden cuttings) and "waste-to-energy" plants has reduced the volume of material going into landfills. The expansion of landfill methane capture projects (both for energy and emissions control), although much slower, has reduced methane emissions from existing sources.
- Coal mine methane emissions are dominated by a relatively small group of underground coal mines. While the coal industry as a whole has been increasing output in recent years, these mines have suffered from vicissitudes particular to their locations, production economics, and the grades of coal they produce. Output from these mines does not necessarily track with national trends. Further, a number of them have introduced methane capture programs, which have also reduced emissions.

Nitrous Oxide

Nitrous oxide emissions estimates are more uncertain than estimates of methane emissions, and the uncertainty of the estimation methods makes it difficult to be confident of apparent trends. The principal sources are believed to be "excess" emissions from agricultural soils associated with fertilizer use, industrial process emissions, and emissions from combustion of fossil fuels. Nitrous oxide emissions, estimated at 0.45 million metric tons in 1996, are essentially unchanged since 1990. Declining agricultural emissions (due to reduced use of nitrogen fertilizers) have offset slowly increasing energy-related and industrial emissions (Figure ES5).

Figure ES5. U.S. Nitrous Oxide Emissions by Source, 1980-1996



Source: EIA estimates documented in Chapter 4 of this report.

Halocarbons and Related Compounds

Halocarbons and related compounds include chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and other compounds that act as greenhouse gases. Halocarbons have many uses, but most emissions come from their use as refrigerants in cooling equipment, as solvents, or as blowing agents and from fugitive emissions in industrial processes.

CFCs are currently being phased out because they damage the stratospheric ozone layer. The warming effects of CFCs and HCFCs are offset to some extent because they also destroy ozone, which is a potent greenhouse gas. Compounds that contain no chlorine (such as HFCs and PFCs) do not affect ozone, and their effects on climate are therefore easier to measure.

The available data suggest that emissions of CFCs—about 0.2 million metric tons in 1990—are declining. Estimated HCFC emissions (almost entirely HCFC-22, a popular refrigerant for home air conditioners) have been largely stable since 1993. There is little information about emissions of "new" HCFCs, such as HCFC-141b and HCFC-142b, which are CFC substitutes.

HFC emissions were very low—perhaps 0.006 million metric tons—in 1990. Emissions of HFC-23, a byproduct of HCFC-22 production, have also been roughly stable since 1993. Emissions of the CFC substitutes HFC-134a and HFC-152 have risen substantially in the past 3 years, from a base total of less than 0.001 million metric tons in 1990 (Figure ES6). HFC-134a became the standard automobile air conditioner refrigerant in 1994, and emissions will grow rapidly as CFCs are replaced throughout the automobile fleet. Consumption of HFC-152 is growing rapidly, but it has a relatively low global warming potential of 140.

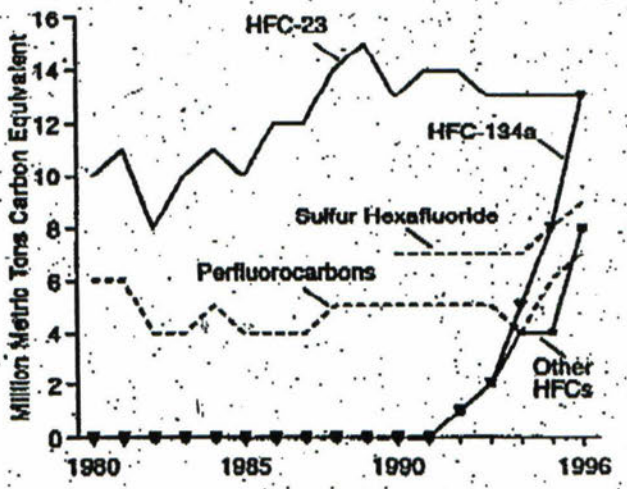
The principal quantifiable source of PFCs is as a fugitive emission from aluminum smelting. Aluminum smelting rebounded in 1996, after declining in the early 1990s, increasing the estimated emissions of PFCs. In recent years, several PFCs have found markets in the semiconductor industry, but it has proved difficult to obtain reliable information about sales and consumption, other than that the numbers are relatively small.

Another compound included in this category is sulfur hexafluoride, which is used primarily as an insulating gas in electrical switchgear. The amounts used are uncertain but appear to be quite small (around 1,000 metric tons per year); however, sulfur hexafluoride has an extremely high global warming potential (around 25,000), and, hence, even small emissions have disproportionate consequences.

Criteria Pollutants

Criteria pollutants (carbon monoxide, nitrogen oxides, and nonmethane volatile organic compounds) are reactive gases that usually decay quickly in the atmosphere. They are not necessarily greenhouse gases themselves, but they can promote atmospheric chemical reactions that create tropospheric ozone, which is a potent greenhouse gas. Because the ozone-creating effect of these gases varies with local atmospheric conditions, it is not possible to compute their effects directly. As precursors to urban "smog," their emissions are regulated under the Clean Air Act. The principal source of emissions of criteria pollutants is the combustion of fossil fuels, particularly in motor vehicles.

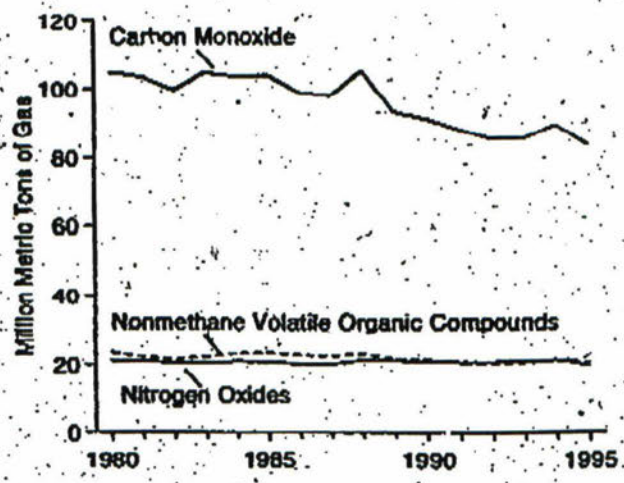
Figure ES6. U.S. Emissions HFCs, PFCs, and Sulfur Hexafluoride, 1980-1996



Source: EIA estimates documented in Chapter 5 of this report.

According to estimates from the U.S. Environmental Protection Agency, national-level emissions of carbon monoxide have been declining since the late 1970s (Figure ES7). Emissions of nonmethane volatile organic

Figure ES7. U.S. Emissions of Selected Criteria Pollutants, 1980-1995



Source: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, *National Air Pollutant Emission Trends, 1900-1995*, EPA-454/96-007 (Research Triangle Park, NC, October 1996), Tables A-1–A-11, pp. A-2–A-16.

compounds and nitrogen oxides have been essentially unchanged in recent years.

Land Use Issues

Changes in land use can also have large, though difficult to quantify, effects on atmospheric concentrations of greenhouse gases. In the United States, the expansion of forest land and the growth of existing forests are responsible for removing large amounts of carbon from the atmosphere. Several studies of carbon sequestration in U.S. forests suggest that in the late 1980s and early 1990s, some 111 to 238 million metric tons of carbon was sequestered annually, equivalent to about 8 to 17 percent of U.S. anthropogenic carbon emissions.[3] However, considerable uncertainty is associated with this estimate—particularly with the amount of carbon sequestered in forest soils.

The IPCC recommends including emissions and sequestration from land use changes in national inventories, and the U.S. "National Communication" for the Framework Convention follows this practice.[4] The EIA, however, has elected not to include carbon sequestration from forestry in its "total" estimate of U.S. emissions, for the following reasons:

- There is insufficient information to determine the extent, if any, of year-to-year changes in anthropogenic sequestration of carbon. Changes in national sequestration rates can be estimated only at 5-year intervals. The current estimate is an annual average for the period 1987-1992; new data will become available in 1998, covering the 1992-1997 period.
- The magnitude of the sequestration estimate is subject to considerable uncertainty on several counts. The largest source of uncertainty is the amount of carbon sequestered annually in forest soils.

[3]R.A. Birdsey and L.S. Heath, "Carbon Changes in U.S. Forests," in L.A. Joyce (ed.), *Productivity of America's Forests and Climate Change* (Fort Collins, CO: USDA Forest Service, General Technical Report RM-GTR-271, 1995).

[4]U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1993*, EPA-230-R-94-014 (Washington, DC, September 1994), p. ES-7.

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FEDERAL ENERGY RESEARCH AND DEVELOPMENT FOR THE CHALLENGES OF THE TWENTY-FIRST CENTURY

REPORT OF THE ENERGY RESEARCH AND DEVELOPMENT PANEL

THE PRESIDENT'S COMMITTEE OF ADVISORS ON SCIENCE AND TECHNOLOGY (PCAST)

SEPTEMBER 30, 1997

EXECUTIVE OFFICE OF THE PRESIDENT
PRESIDENT'S COMMITTEE OF ADVISORS ON SCIENCE AND TECHNOLOGY
WASHINGTON, D.C. 20500

September 30, 1997

President William J. Clinton
The White House
1600 Pennsylvania Avenue N.W.
Washington, DC 20500

Dear Mr. President:

I am pleased to transmit on behalf of the President's Committee of Advisors on Science and Technology (PCAST) the Executive Summary of our report *Federal Energy Research and Development for the Challenges of the 21st Century.* This Executive Summary, unanimously approved by the PCAST, is in response to your January 14, 1997, letter to me as PCAST Co-Chair requesting a review of the current national energy R&D portfolio. You asked for recommendations by October 1 on how to ensure that the United States has a program that addresses its energy and environmental needs for the next century.

PCAST endorses the report's findings that this country's economic prosperity, environmental quality, national security, and world leadership in science and technology all require improving our energy technologies, and that an enhanced national R&D effort is needed to provide these improvements. The inadequacy of current energy R&D is especially acute in relation to the challenge of responding responsibly and cost-effectively to the risk of global climatic change from society's greenhouse gas emissions, in particular, carbon dioxide from combustion of fossil fuels.

We recommend focusing the government's energy R&D on projects where high potential payoffs for society as a whole justify bigger R&D investments than industry would be likely to make on the basis of expected private returns and where modest government investments can effectively complement, leverage, or catalyze work in the private sector.

The report recommends an increase, over a five-year period, of $1 billion in the Department of Energy's annual budget for applied energy-technology R&D. The largest shares of such an increase would go to R&D in energy efficiency and renewable energy technologies, but nuclear fusion and fission would also receive increases. The composition of the R&D supported on advanced fossil-fuel technologies would change in favor of longer-term opportunities, including fuel cells and carbon-sequestration technologies, but the overall spending level for fossil-fuel technologies would stay roughly constant in real terms.

The proposed total for FY 2003 would return the DOE's real level of effort in applied energy-technology R&D in that year to about where it was in FY 1991 and FY 1992. In constant dollars, the average real growth rate would be 8.3 percent per year.

We respectfully urge, further, that you increase your efforts to communicate clearly to the public the importance of energy and energy R&D to the nation's future, and we recommend that you clearly designate the Secretary of Energy as the national leader and coordinator for developing and carrying out the national energy strategy.

The report also makes recommendations for improving the Department of Energy's management of its energy R&D portfolio, including the naming of a single individual with responsibility for the whole portfolio and reporting directly to the Secretary.

PCAST hopes that these recommendations will be helpful to you as you consider how the United States can best face major energy related challenges as it enters the 21st century. Of particular importance, prudence requires having in place an adequate energy R&D effort designed to expand the array of technological options to enable significant reductions in greenhouse gases at the lowest possible economic, environmental, and social cost.

The energy R&D portfolio we propose will be of crucial importance in meeting that challenge. Many of the energy-technologies that will help with the problem of climate change, moreover, will also help address other energy-related challenges, including reducing dependence on imported oil, diversifying the U.S. domestic fuel- and electricity-supply systems, expanding U.S. exports of energy technologies, reducing air and water pollution, and reducing the cost, safety and security risks of nuclear energy systems around the world.

Sincerely,

John A. Young
Co-Chairman
President's Committee of Advisors on Science and Technology

cc: Vice President Al Gore

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Study Executive Director

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National Science and
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Ambuj Sagar
Harvard University

This was a Panel of twenty-one persons of diverse backgrounds and viewpoints, tackling an immensely complex subject. Inevitably, not every member of the Panel is entirely happy with every formulation in the report. But we are unanimous that the main messages and overall balance in this joint product are correct and appropriate.

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Federal Energy Research and Development for the Challenges of the Twenty-First Century

Panel on Federal Energy R&D,
President's Committee of Advisors on Science and Technology
Executive Office of the President of the United States

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EXECUTIVE SUMMARY

The United States faces major energy-related challenges as it enters the twenty-first century. Our economic well-being depends on reliable, affordable supplies of energy. Our environmental well-being — from improving urban air quality to abating the risk of global warming — requires a mix of energy sources that emits less carbon dioxide and other pollutants than today's mix does. Our national security requires secure supplies of oil or alternatives to it, as well as prevention of nuclear proliferation. And for reasons of economy, environment, security, and stature as a world power alike, the United States must maintain its leadership in the science and technology of energy supply and use.

All of these energy-related challenges to the well-being of this country are made more acute by what is happening elsewhere in the world. The combination of population growth and economic development in Asia, Africa, and Latin America is driving a rapid expansion of world energy use, which is beginning to augment significantly the worldwide emissions of carbon dioxide from fossil-fuel combustion, increasing pressures on world oil supplies, and exacerbating nuclear proliferation concerns. Means must be found to meet the economic aspirations and associated energy needs of all the world's people while protecting the environment and preserving peace, stability, and opportunity.

Improvements in energy technologies, attainable through energy research and development, are the key to the capacity of the United States to address — and to help the rest of the world address — these challenges.

Many of the energy R&D programs of the Federal government, which are primarily conducted by the Department of Energy (DOE), have been well focused and effective within the limits of available funding. But these programs, taken as a whole, are not commensurate in scope and scale with the energy challenges and opportunities the twenty-first century will present. (This judgment takes into account the contributions to energy R&D that can reasonably be expected to be made by the private sector under market conditions similar to today's.) The inadequacy of current energy R&D is especially acute in relation to the challenge of responding prudently and cost-effectively to the risk of global climatic change from society's greenhouse-gas emissions, of which the most important is carbon dioxide from combustion of fossil fuels. Much of the new R&D needed to respond to this challenge would also be responsive to the other challenges.

SYNOPSIS OF MAIN RECOMMENDATIONS

To close the gap between the current energy R&D program and the one that the challenges require, the Panel recommends strengthening the DOE applied energy-technology R&D portfolio by increasing funding for four of its major elements (energy end-use efficiency, nuclear fission, nuclear fusion, and renewable energy technologies) and restructuring part of the fifth (fossil-fuel technologies). We also recommend better coordination between the Department's applied energy-technology programs and the fundamental research carried out in the program on Basic Energy Sciences; increased Department efforts in integrated analysis of its entire energy R&D portfolio and the leverage the portfolio offers against the energy challenges of the next century; targeted efforts to improve the prospects of commercialization of the fruits of publicly funded energy R&D in specific areas; increased attention to certain international aspects of energy R&D; and changes in the prominence given to energy R&D in relation to the Department's other missions, coupled with changes in how this R&D is managed.

Applied Energy-Technology R&D Recommendations

The overall budgets we propose for applied energy-technology R&D to the year 2003, based on analyses summarized in our main report and set out in more detail in its appendices, are summarized in Table ES-1. (The table provides these figures both in as-spent dollars, which are the usual currency of official budget planning, and in constant 1997 dollars, which are more informative about what is really happening to the size of the effort.)

The applied energy-technology R&D programs, which have been the main focus of the Panel's study and which are shown in Table ES-1, contain only part of the activities constituting DOE's Congressional budget lines for "Energy R&D". Table ES-2 shows the relation, under the FY 1997 Congressional appropriation and the FY 1998 DOE request, between the amount budgeted for the activities included in our "applied energy-technology R&D" category and the amounts budgeted for the other activities included under "Energy R&D" in the Congressional budget lines.

The Panel was not able to review in detail the Basic Energy Sciences budget line (which includes research in materials science, chemistry, applied mathematics, biosciences, geosciences, and engineering that is not directed at the development of a particular class of energy sources), and it did not review at all the other "Energy R&D" budget lines shown in Table ES-2 (which contain mostly items that are either not very closely linked to advances in civilian energy technology or are not really R&D at all). Accordingly, we do not offer any recommendations about the future sizes of these budgets. We note, however, that because advances produced by research in the Basic Energy Sciences (BES) category provide an important part of the expanding knowledge base on which progress in applied energy-technology R&D in the public and private sectors alike depends, the Department may want to consider expanding its support for BES as the applied energy-technology R&D areas grow.

As indicated in Table ES-1, our proposals for the applied energy-technology R&D programs would increase spending in that category from $1.3 billion in 1997 to $2.4 billion in 2003, in as-spent dollars. In constant-dollar terms, the increase from 1997 through 2003 is 61 percent, amounting to an average real growth rate of 8.3 percent per year. The proposed figure

for 2003 would return the DOE's real level of effort in applied energy-technology R&D in that year to about where it was in FY 1991 and FY 1992.

Table ES-1. **Recommended DOE Budget Authority for Applied Energy-Technology R&D**

In millions of as-spent dollars

	1997 actual	1998 request	1999	2000	2001	2002	2003
Efficiency	373	454	615	690	770	820	880
Fission	42	46	66	86	101	116	119
Fossil	365	346	379	406	433	437	433
Fusion	232	225	250	270	290	320	328
Renewables	270	345	475	585	620	636	652
TOTAL AET	1282	1416	1785	2037	2214	2329	2412

In millions of constant 1997 dollars

	1997 actual	1998 request	1999	2000	2001	2002	2003
Efficiency	373	442	584	638	695	721	755
Fission	42	45	63	80	91	102	102
Fossil	365	337	360	376	391	384	371
Fusion	232	219	237	250	262	281	281
Renewables	270	336	451	541	559	559	559
TOTAL AET	1282	1379	1695	1885	1998	2047	2068

Note: What is called "energy end-use efficiency" in this report and is abbreviated as "efficiency" in these tables appears as "conservation" in many budget documents.

Of the Panel's proposed increases in DOE's applied energy-technology R&D accounts, the largest in dollar magnitude is in the end-use-efficiency programs, in which annual spending in FY 2003 would reach $880 million, about $500 million more than in 1997 (as-spent dollars). This large increase is appropriate because of the high promise of advanced efficiency technologies for relatively quick-starting and rapidly expanding contributions to several important societal goals, including cost-effective reductions in local air pollution and carbon-dioxide emissions, diminished dependence on imported oil, and reductions in energy costs to households and firms.

Improvements in energy efficiency reduced the energy intensity of economic activity in the United States by nearly one-third between 1975 and 1995, an improvement that is now saving U.S. consumers about $170 billion per year in energy expenditures and is keeping U.S. emissions of air pollutants and carbon dioxide about a third lower than they would otherwise be.

Table ES-2. **Relation of Applied Energy Technology R&D to "Total Energy R&D"**

In millions of as-spent dollars.

	1997 actual	1998 request
APPLIED ENERGY TECHNOLOGY R&D	1282	1416
"Energy Research": Basic Energy Sciences	641	661
"Energy Research": Other Non-Fusion	539	585
"Other Nuclear R&D"	216	255
"Other Conservation R&D"	177	234
TOTAL "ENERGY R&D" BUDGET LINES	2855	3151

Notes: DOE's Office of Energy Research includes the Department's R&D on fusion energy, as well as Basic Energy Sciences and some other science and technology programs including biomedical and environmental research, research in computing, and science education. "Other Conservation R&D" includes the State and Local Partnership Programs and the Federal Energy Management Program (which are not really R&D at all), among other items. "Other Nuclear R&D" includes radioisotope power sources for spacecraft and isotopes for medical applications, among other items. The Panel included fusion in its analysis of applied energy-technology R&D (although, as noted in that analysis, much fusion R&D is in fact basic science).

Further major increases in efficiency can be achieved in every energy end-use sector: in transportation, for example, through much more fuel-efficient cars and trucks; in industry through improved electric motors, materials-processing technologies, and manufacturing processes; in residential and commercial buildings through high-technology windows, super-insulation, more efficient lighting, and advanced heating and cooling systems.

The second largest of the Panel's proposed increases is for renewable energy technologies, in which annual spending in FY 2003 would reach $650 million, nearly $400 million more than in 1997 (as-spent dollars). This increase makes sense in light of the rapid rate of cost reduction achieved in recent years for a number of renewable energy technologies, the good prospects for further gains, and the substantial positive contributions these technologies could make to improving environmental quality, reducing the risk of climate change, controlling oil-import growth, and promoting sustainable economic development in Africa, Asia, and Latin America.

Opportunities exist for important advances in wind-electric systems, photovoltaics, solar-thermal energy systems, biomass-energy technologies for fuel and electricity, geothermal energy, and a range of hydrogen-producing and hydrogen-using technologies including fuel cells. As in the case of the proposed increases in energy-efficiency R&D we propose, the increased support for these renewable-energy technologies would focus on areas where the expected short-term returns to industry are insufficient to stimulate as much R&D as the public benefits warrant.

Fusion R&D is proposed for the third largest increase: annual spending for it in FY 2003 would reach about $100 million more than the 1997 figure in as-spent dollars. In this scenario, fusion funding would reach by 2002 the $320 million figure recommended in the 1995 PCAST

study of fusion-energy R&D as a constant level of spending in as-spent dollars to be maintained from FY 1996 onward. (This earlier PCAST recommendation did not prevail, and fusion funding fell instead from $369 million in FY 1995 to $232 million in FY 1997.)

The Panel judges this amount warranted for two reasons: (1) About $200 million per year of it would continue a very productive element of the country's basic science portfolio (comparing favorably in cutting-edge contributions and valuable spinoffs with other fields in that category); and (2) the rest is easily justified as the sort of investment the government should be making in a high-risk but potentially very-high-yield energy option for society, in which the size and time horizon of the program essentially rule out private funding.

DOE's R&D in nuclear-fission energy systems, which fell 12-fold in real terms between 1986 and 1997, would increase under our proposal from about $40 million per year in FY 1997 to about $120 million per year in 2003 (as-spent dollars), thereby returning in real level of effort to that of 1995. Nuclear fission currently generates about 17 percent of the world's electricity; if this electricity were generated instead by coal, world carbon dioxide emissions from fossil-fuel consumption would be almost 10 percent larger than they currently are.

Fission's future expandability is in doubt in the United States and many other regions of the world because of concerns about high costs, reactor-accident risks, radioactive-waste management, and potential links to the spread of nuclear weapons. We believe that the potential benefits of an expanded contribution from fission in helping address the carbon-dioxide challenge warrant the modest research initiative proposed here, in order to find out whether and how improved technology could alleviate the concerns that cloud this energy option's future. To write off fission now as some have suggested, instead of trying to fix it where it is impaired, would be imprudent in energy terms and would risk losing much U.S. influence over the safety and proliferation resistance of nuclear-energy activities in other countries. Fission belongs in the R&D portfolio.

Energy from fossil fuels currently contributes 85 percent of U.S. annual energy use and 75 percent of the world's. These fuels will continue to provide immense amounts of energy through the middle of the next century and beyond, under any plausible scenario. We judge that DOE's current fossil-energy R&D program is about the appropriate size in relation to the array of relevant needs, opportunities, and likely continuing private-sector fossil-energy R&D activities. Our proposed budget for DOE's fossil-energy R&D, which increases funding in as-spent dollars by about $70 million per year between 1997 and 2003, actually holds the real level of effort approximately level near its FY 1997 value of $365 million per year.

We do, however, recommend some changes in emphasis within this program. Specifically, we propose phasing out DOE's R&D on near-term coal-power technologies and promptly ending the funding for direct coal liquefaction, while increasing the Department's R&D on advanced coal-power programs, carbon capture and sequestration, fuel cells and other hydrogen technology, and advanced oil and gas production and processing. These changes are designed to increase the responsiveness of DOE's fossil-energy R&D to the carbon-dioxide and oil-import challenges (including technology export opportunities that could favorably affect other countries' carbon emissions and oil imports while improving the U.S. balance of payments), and to improve the program's complementarity with (or help to stimulate) R&D efforts in the private sector.

Our recommendations for R&D initiatives in the efficiency, renewables, fusion, fission, and fossil-fuel components of DOE's applied energy-technology portfolio are described in more detail later in this Executive Summary and are summarized, together with the budgets we propose for these efforts, in Table ES-3.

Recommendations on Cross-Cutting Issues

The Panel recommends that coordination between the Basic Energy Sciences program and the applied energy-technology programs be improved using mechanisms such as co-management and co-funding.

We recommend that the Department make a much more systematic effort in R&D portfolio analysis: portraying the diverse characteristics of different energy options in a way that facilitates comparisons and the development of appropriate portfolio balance, in light of the challenges facing energy R&D and in light of the nature of private-sector and international efforts and the interaction of U.S. government R&D with them.

After consideration of the market circumstances and public benefits associated with the energy-technology options for which we have recommended increased R&D, the Panel recommends that the nation adopt a commercialization strategy in specific areas complementing its public investments in R&D. This strategy should be designed to reduce the prices of the targeted technologies to competitive levels, and it should be limited in cost and duration.

The Panel recommends that the government and government/national-laboratory/industry/university consortia should engage strongly in international energy technology R&D and, where appropriate, development and commercialization efforts to regain and/or maintain the scientific, technical, and market leadership of the United States in energy technology.

We recommend that overall responsibility for DOE energy R&D portfolio should be assigned to a single person reporting directly to the Secretary of Energy, and that, similarly, a single individual should be given the responsibility and authority for coordination of cross-cutting programs between the applied-technology programs, reporting to the single person responsible for the overall R&D portfolio.

The Panel recommends that industry/national-laboratory-university oversight committees should work with DOE to provide overall direction to energy R&D programs, with DOE facilitating and administering the process; and we recommend that all DOE energy R&D programs undergo outside technical peer review every 1-2 years, while interim internal process-oriented reviews are reduced to a minimum.

Additional recommendations and discussion on cross-cutting issues appear later in this Executive Summary.

RATIONALE FOR THE RECOMMENDATIONS

The rationale for the recommendations summarized above — and for others to be found in the more detailed treatment later in this Executive Summary — is presented in what follows in terms of the importance of energy to our national well-being, the evolution of U.S. and world energy supply and demand, the challenges this evolution poses to energy R&D, recent trends in public and private funding for energy R&D, and the implications of those trends (and the energy R&D status quo) for the prospects of meeting the energy and environmental challenges of the next century.

The Importance of Energy

The characteristics of the technologies available to this nation and others for energy supply and energy end-use are critical to our country's economic well-being, environmental quality, and national security:

- Economically, expenditures on energy account for 7 to 8 percent of gross economic product in the United States and worldwide and a similar fraction of the value of U.S. and world trade. Experience has shown that periods of excessive energy costs are associated with inflation, recession, and frustrated economic aspirations. Sales of new energy-supply technologies globally run in the multi-hundreds of billions of dollars per year.

- Environmentally, energy supply accounts for a large share of the most worrisome environmental problems at every geographic scale — from wood-smoke in Third World village huts, to regional smogs and acid precipitation in industrialized and developing countries alike, to the risk of widespread radioactive contamination from accidents at nuclear-energy facilities, to the build-up of carbon dioxide and other heat-trapping gases in the global atmosphere.

- National security is linked to energy through the increasing dependence of this country and many others on imported oil, much of it from the politically troubled Middle East; through the danger that nuclear-weapons-relevant knowledge and materials will be transferred from civilian nuclear-energy programs into national nuclear arsenals or terrorist bombs; and through the potential for large-scale failures of energy strategy with economic or environmental consequences serious enough to generate or aggravate social and political instability.

Scientific and technological progress, achieved through R&D, is crucial to minimizing current and future difficulties associated with these interactions between energy and well-being, and crucial to maximizing the opportunities. If the pace of such progress is not sufficient, the future will be less prosperous economically, more afflicted environmentally, and more burdened with conflict than most people expect. And if the pace of progress is sufficient elsewhere but not in the United States, this country's position of scientific and technological leadership — and with it much of the basis of our economic competitiveness, our military security, and our leadership in world affairs — will be compromised.

Past, Present, and Projected Patterns of Energy Supply

The challenges and opportunities associated with the economic, environmental, and national-security dimensions of energy have become what they are primarily as a consequence of the tremendous increase in energy use, and especially fossil-fuel use, over the past century and a half. This increase, in which world energy use grew 20-fold between 1850 and 1995 and fossil-fuel use increased more than 100-fold, arose principally from the combination of population growth and rapid economic development in the industrialized countries.

In contrast, by far the largest part of the *future* growth of world energy use is expected to take place in the currently less developed countries of Asia, Africa, and Latin America. Today, with nearly 80 percent of the world's population, these countries still account for only a third of the energy use. But if recent trends continue (the "business as usual" energy future), they will pass the industrialized countries in total energy use (and in carbon dioxide emissions) between 2020 and 2030, and their growth will be the primary driver of a doubling in global energy use between 1995 and 2030 and a quadrupling between 1995 and 2100.

Energy use in industrialized countries would continue to increase in a business-as-usual future, but not as rapidly as in the less developed countries and not as rapidly as in the past. A business-as-usual energy trajectory for the United States would entail increases in energy use, above the 1995 level, of about 40 percent by 2030 and nearly 75 percent by 2100.

The fossil fuels — oil, natural gas, and coal — accounted for 75 percent of energy supply worldwide in 1995. The remainder was nuclear energy (6 percent), hydropower (6 percent), and biomass fuels (13 percent, mostly fuel-wood in developing countries), with wind, solar, and geothermal energy together contributing less than half a percent. The dominance of the fossil fuels would decline only slowly in a business-as-usual future: the world as a whole would still be obtaining perhaps two-thirds of all its energy needs from fossil fuels in 2030 and half or more in 2100. Fossil-fuel resources are adequate to support such an outcome, albeit perhaps with higher dependence on coal than today, relative to oil and gas.

The United States obtained 85 percent of its energy from fossil fuels in 1995, nearly 40 percent from oil alone (of which half was imported). U.S. fossil-fuel dependence, like that of the rest of the world, would decline only slowly in a business-as-usual future. U.S. oil imports, according to the "reference" forecast of the Department of Energy, would grow from 9 million barrels per day in 1995 to 14 million barrels per day in 2015 and continue to increase for some time thereafter.

The Challenge to Energy R&D

Improvements in energy technology can and must play a major role in reducing the costs, increasing the benefits, and alleviating the perils that a business-as-usual energy future without such improvements would be likely to entail.

Energy-technology improvements, achieved in the United States and then deployed here and elsewhere, could

- lower the monetary costs of supplying energy,
- lower its effective costs still further by increasing the efficiency of its end uses,
- increase the productivity of U.S. manufacturing,
- increase U.S. exports of high-technology energy-supply and energy-end-use products and know-how,
- reduce over-dependence on oil imports here and in other countries, thus reducing the risk of oil-price shocks and alleviating a potential source of conflict,
- diversify the domestic fuel-supply and electricity-supply portfolios to build resilience against the shocks and surprises that an uncertain future is likely to deliver,
- reduce the emissions of air pollutants hazardous to human health and to ecosystems,
- improve the safety and proliferation resistance of nuclear energy operations around the world,
- slow the build-up of heat-trapping gases in the global atmosphere, and
- enhance the prospects for environmentally sustainable and politically stabilizing economic development in the many of the world's potential trouble spots.

The direct and indirect effects of the pursuit of improved energy technologies for these purposes through appropriately sized, tailored, and publicized R&D programs, moreover, will strengthen this country's science and technology base, bolster our research universities, build effective industry-government-university partnerships, help to stem the decline in enrollments of our most talented young people in science and engineering disciplines, and contribute to maintaining the global leadership and influence of the United States in relation to scientific and technological developments worldwide and their application to the betterment of the human condition.

Among all of these good reasons for adequately funded, suitably focused, effectively managed energy R&D, one is particularly demanding in what it requires of the R&D effort: the need to expand the array of energy technologies available for responding cost-effectively to the risk of global climatic change from greenhouse gases, most importantly carbon dioxide from fossil-fuel combustion.

Many of the characteristics of this risk and of society's potential responses to it are subject to considerable uncertainty and controversy. These characteristics aspects include the pace at which climatic change may become more obvious as greenhouse-gas concentrations grow, the magnitude and geographic distribution of the ecological and human consequences of such change, and the impacts on the U.S. and world economies of various measures that might be undertaken to constrain carbon-dioxide emissions.

If greenhouse-gas-induced climate change were to develop along the path deemed most likely in the latest assessment by the Intergovernmental Panel on Climate Change (IPCC), there would be a significant chance that changes in patterns of temperature, humidity, rainfall, soil moisture, and ocean circulation, plus increases in sea level, would be adversely impacting human well-being over substantial areas of the planet by some time in the twenty-first century. The IPCC assessment also indicates that slowing the build-up of carbon dioxide in the atmosphere will be very difficult to achieve, because of the upward pressure of population growth and economic aspirations on energy demand, the large energy contribution and long turnover time of the fossil-fuel technologies that are the primary source of CO_2 emissions, and the long residence time of this gas in the atmosphere.

Of course, the work of the IPCC to date will not be the last word on the issue of greenhouse-gas-induced climate change. Some members of the research community think the IPCC's projections of future climate change and its consequences are too pessimistic. Others think they are too optimistic. And some contend that adaptation to climate change would be less difficult and less costly than trying to prevent the change, whereas others argue that a strategy combining prevention and adaptation is likely to be both cheaper and safer than one relying on adaptation alone. Within our own Panel there are significant differences of view on some of these questions.

Notwithstanding these differences, however, the Panel members are in complete agreement about the implications of the climate-change issue for energy R&D strategy:

- First, there is a significant possibility that governments will decide, in light of the perceived risks of greenhouse-gas-induced climate change and the perceived benefits of a mixed prevention/adaptation strategy, that emissions of greenhouse gases from energy systems should be reduced substantially and soon. Prudence therefore requires having in place an adequate energy R&D effort designed to expand the array of technological options available for accomplishing this at the lowest possible economic, environmental, and social cost;

- Second, because of the large role of fossil-fuel technologies in the current U.S. and world energy systems, the technical difficulty and cost of modifying these technologies reduce their carbon dioxide emissions, their long turnover times, their economic attractiveness compared to most of the currently available alternatives, and the long times typically required to develop new alternatives to the point of commercialization, the possibility of a mandate to significantly constrain greenhouse-gas emissions is the most demanding of all of the looming energy challenges in what it requires of national and international energy R&D efforts.

- Third (and this finally is the *good* news about the greenhouse-gas issue), many of the energy-technology improvements that would be attractive for this purpose also could contribute importantly to addressing some of the other energy-related challenges that lie ahead, including reducing dependence on imported oil, diversifying the U.S. domestic fuel- and electricity-supply systems, expanding U.S. exports of energy-supply and energy-end-use technologies and know-how, reducing air and water pollution from fossil-fuel technologies, reducing the cost and safety and security risks of nuclear energy systems

around the world, fostering sustainable and stabilizing economic development, and strengthening U.S. leadership in science and technology.

Energy R&D Spending in Decline

Society's capacity to respond effectively to the challenges described above will be determined in large measure by the *output* of its energy R&D efforts (as well as to the success of measures undertaken to ensure that the output is effectively deployed); and the output of R&D efforts will be substantially affected (with variations depending on the efficiency with which the R&D is managed and conducted) by the *input*, that is, by R&D spending.

Nonetheless, while the challenges looming in the energy futures of the United States and the world have been growing in recent years — or at least growing more apparent — expenditures on R&D have been declining. In the United States, this has been the case in both the public and the private sectors, although the decline in funding from the public sector has been considerably steeper than the decline in funding from industry. Government funding for energy R&D has also been falling in most other industrialized countries, with the conspicuous exception of Japan. (The Panel was not able to compile plausible estimates of trends in private-sector R&D funding in other countries.)

By far the largest part of Federal funding for energy R&D (about 90 percent) comes from DOE. The Department's FY 1997 budget for applied energy-technology R&D was $1.28 billion, compared to $2.18 billion five years earlier, in FY 1992, and $6.15 billion twenty years earlier, in FY 1978 (all figures in constant 1997 dollars).

If one includes DOE's funding for Basic Energy Sciences, the energy R&D decline was from $6.55 billion in FY 1978 to $3.04 billion in FY 1992 to $1.92 billion in FY 1997. Thus the decrease in the past 5 years was between 37 and 42 percent, depending on whether BES is included in the totals, and the decrease between 1978 and 1997 was between 3.4- and 4.8-fold. As a fraction of real GDP, DOE's 1997 spending for energy-technology was less than half that of DOE's predecessor agencies 30 years earlier, in 1967, at the height of pre-oil-shock American complacency about energy supply and energy prices.

Although data for energy R&D in the U.S. private sector are less comprehensive than those for government spending, the most recent systematic study of energy-industry R&D trends found that the industry's spending for R&D fell 40 percent in real terms between 1985 and 1994, from $4.4 billion to $2.6 billion. The R&D spending of the 112 largest U.S. operating electric utilities fell 38 percent between 1993 and 1996 alone, and the R&D of the four U.S. oil firms with the largest research efforts approximately halved between 1990 and 1996.

There is evidence that Federal and private investments in R&D in general (that is, not for energy alone) tend to rise and fall together, rather than one's rising in compensation when the other goes down. State-government funding of energy R&D in the United States, which was probably under $200 million in 1995, may follow electric-utility funding downward.

In the G-7 countries other than the United States and Japan, public-sector energy R&D has fallen sharply, decreasing between 1984 and 1994 by more than 4-fold in both Germany and

Italy, by about 6-fold in the United Kingdom, and by 2-fold in Canada. Public spending on energy R&D in France, for which 1984 figures were not available, was declining slowly between 1990 and 1995. Japan, however, increased its public-sector energy R&D spending from about $1.5 billion in 1974 to $4.2 billion in 1980; by 1995 the figure was $4.9 billion, about twice as high as DOE's energy R&D spending (BES included) in that year.

Explanations and Implications of the Declines in Public and Private R&D

Many explanations for the overall downward trends in energy R&D in recent years suggest themselves. One important factor is surely low energy prices. World oil prices fell sharply after 1980, and in the 1990s they have been about where they were in the 1920s and in the 1950s (in inflation-corrected dollars); and natural gas prices in the United States are so low that no other means of electricity generation can compete with gas-fired combined-cycle power plants where gas is available. This situation discourages investment in the development of new energy technologies. The very large demonstration projects in fossil, nuclear, and renewable energy that accounted for much of the post-oil-shock increase in U.S. Federal energy R&D spending came to be regarded as costly anachronisms after prices fell again, and their cancellation was, for the most part, appropriate.

In addition, public-sector spending on energy R&D has experienced downward pressure from overall budgetary stringency in government and from public and policy-maker complacency attributable to low prices, no gasoline lines, and high confidence in the capacity of the United States and allied military forces to preserve access to Middle East oil. DOE has experienced particular budget-inhibiting scrutiny by critics of "big government", and its energy R&D spending has been further constrained from within by pressure from larger parts of the Department's budget (notably environmental cleanup and nuclear-weapons programs).

In the competitive environment of declining government spending on energy R&D, moreover, advocates of each energy option have tended to disparage the prospects of the other options, in hopes of gaining a greater share of the budget for their favorite. Thus the energy community itself has formulated the arguments that budget-cutters have used to downsize energy R&D programs one at a time ("renewables are too costly", "fossil fuels are too dirty", "nuclear fission is too risky", "fusion will never work", "conservation means sacrifice"), with no coherent energy-community voice calling for a responsible portfolio approach to energy R&D — that is, an approach that seeks to address and ameliorate the shortcomings of all of the options.

The private sector, meanwhile, has been experiencing a paradigm shift driven by the increasing globalization of the economy, the revolution in information technology, the increasing power of shareholders and financial markets over corporate decisions, and deregulation and restructuring in important parts of the energy business. These factors have combined with low energy prices and the inherently low profit margins of commodity-based businesses to cause energy companies to place more emphasis on the short-term bottom line, to decrease risk taking on broad-based or long-range R&D projects, and to outsource their R&D to specialized R&D contractors (which may represent a part of private-sector energy R&D that is *not* shrinking).

It is also possible, finally, that energy R&D in the private sector, the public sector, or both has become more efficient, in which case declining inputs (funding) need not mean

correspondingly declining outputs (innovations that can be successfully marketed or that otherwise improve the human condition). The Panel hopes that this is so, although it is difficult to verify (partly because there are often significant time lags between the conduct of research and its effects on the actual flow of innovations, so that if outputs remained high while inputs fell this might be a temporary condition).

In any case, that the overall declines in both public-sector and private-sector funding for R&D are largely explainable, and that some of what has disappeared was not needed or effective, does not establish whether what remains is adequate in relation to current and future needs.

In the private sector, energy R&D has been an important engine of progress, enabling firms to improve their products and invent new ones, so as to increase their shares of existing markets, establish and penetrate new ones, and maintain or increase performance while reducing costs. Perhaps these benefits will flow in adequate measure from the new paradigm; but it is also possible that important parts of an industrial R&D system that has served our society extremely well for many decades are now being sacrificed for short-term gain. Concerns have been expressed that the trend toward decentralization of industrial R&D, for example, could erode the interconnectedness among people and among different bodies of knowledge that contributes much to technological innovation in the long term.

Public-sector R&D funding has the responsibility for addressing needs and opportunities where the potential benefits to society warrant a greater investment than the prospective returns to the private sector can elicit. Such needs and opportunities relate to public goods (such as the national-security benefits of limiting dependence on foreign oil), externalities (such as unpenalized and unregulated environmental impacts), and situations where lack of appropriability of the research results, or the structure of the market, or the size of the risk, or the scale of the investment, or the length of the time horizon before potential gains can be realized dilute incentives for firms to conduct R&D that would greatly benefit society as a whole.

Needs for public-sector R&D can increase over time if the public-goods and externality challenges grow or if changing conditions shrink the incentives of firms to conduct some kinds of R&D that promise high returns to society. We have said enough already to suggest that both things might recently have been happening. But the real test of whether the current portfolio of public energy R&D is adequate comes from asking whether the R&D programs in the portfolio are addressing, effectively and efficiently, all of the needs and opportunities where the prospects of substantial societal benefits are good and the prospective returns to the private sector are insufficient to elicit the needed R&D. The Panel has analyzed DOE's energy R&D portfolio in these terms.

ELABORATION OF FINDINGS AND RECOMMENDATIONS

We turn now to what we found, first in relation to the content of the portfolio's major energy-technology compartments — end-use efficiency, fossil-fuel technologies, nuclear technologies (fission and fusion), and renewable-energy technologies — and then in relation to cross-cutting issues including the role of Basic Energy Sciences, portfolio analysis, commercialization considerations, international dimensions, and DOE management of its energy R&D programs.

End-Use-Efficiency Technology

Between 1975 and 1986, the United States increased its energy efficiency by almost a third. This extraordinary achievement helped pull the country out of its two oil shocks and their attendant stagflation. Efficiency improvements now save U.S. consumers some $170 billion per year; and U.S. emissions of air pollution and CO_2 have been reduced by a third or more from their expected values.

Challenges and Opportunities

Those achievements are instructive as we look at future energy, economic, and environmental issues. Technological advances and investments in energy efficiency helped rescue the U.S. economy once, and gave the country decades of breathing room to deal with the energy problem. Many of these advances were made possible by DOE-sponsored R&D. Can a similar improvement be achieved in the years ahead?

The Panel believes it can. We find that investments in energy efficiency are generally the most cost-effective way to simultaneously reduce the risks of climate change, world oil-supply interruptions, and local air pollution, and to improve the productivity of the economy. We have reviewed technologies that can reduce energy use in automobiles by half or more; in motors and drive systems by half; and in buildings by over 70 percent. Many of these technologies are in their infancy, and require a serious R&D effort to make them commercially viable. Others are near market readiness, but need standards and incentives to ensure they spread rapidly.

Budget, Goals, and Initiatives

The Panel recommends that the R&D components of the DOE's energy efficiency budget grow steadily over the next 5 years, from $373 million to $755 million (constant 1997$). The Panel has identified the following goals (some pre-existing, and some newly proposed hee) for each of the sectors:

Buildings. To fund and carry-out research on equipment, materials, electronic and other related technologies and work in partnership with industry, universities, and state and local governments to enable by 2010: (1) the constructing of 1 million zero-net-energy buildings; and (2) the construction of all new buildings with an average 25-percent increase in energy efficiency as compared to a new building in 1996. Additional longer term research in advanced energy systems and components will enable all new construction to average 70 percent reductions and all renovations to average 50 percent reductions in greenhouse-gas emissions by 2030.

Industry. By 2005, develop with industry a more than 40-percent efficient microturbine (40 to 300 kW), and introduce a 50-percent efficient microturbine by 2010. By 2005, develop with industry and commercially introduce advanced materials for combustion systems to reduce emissions of nitrogen oxides by 30 to 50 percent while increasing efficiency

5 to 10 percent. By 2010, achieve a more than one-fourth improvement in energy intensity of the major energy- consuming industries (forest products, steel, aluminum, metal casting, chemicals, petroluem refining, and glass) and by 2020 a 20 percent improvement in energy efficiency and emissions of the next generation of these industries.

Transportation. By 2004, develop with industry an 80-mile-per-gallon production prototype passenger car (existing goal of the Partnership for a New Generation of Vehicles — PNGV). By 2005, introduce a 10-mpg heavy truck (Classes 7 and 8) with ultra low emissions and the ability to use different fuels (existing goal); and achieve 13 mpg by 2010. By 2010, have a production prototype of a 100-mpg passenger car with zero equivalent emissions. By 2010, achieve at least a tripling in the fuel economy of Class 1-2 trucks, and double the fuel economy of Class 3-6 trucks.

The R&D areas requiring increased funding to meet these goals have been identified. The Department has a sufficiently rich agenda, management expertise, history of success, and most important, potential for future contribution, to justify these increases.

Further Findings and Recommendations

The buildings program needs high-profile leadership from within the Administration, closer links with industry, and better mechanisms to distribute its research results. These elements could be brought together in the "Buildings for the 21st Century Initiative." The codes and standards program needs to be expanded to give greater technical assistance to states and to speed internal progress.

The industries program is effective. It should be expanded to include more industries, and the crosscutting research — which develops technologies for use in many industries — should grow significantly.

Transportation research, most notably the PNGV, is extremely valuable. The PNGV program is insufficiently funded and cannot meet all its goals at current levels. It should be complemented by a "PNGV II" to augment efforts on long-term technologies, such as fuel cells, with extraordinary potential after 2005. PNGV also needs to give greater attention to air-quality issues, to ensure that technologies selected do not undermine national and state clean-air programs. The Administration must also develop new transportation policies that shift the auto fleet, over time, toward higher efficiency. And advanced vehicle development programs should be coordinated with alternative fuels programs to ensure they are complementary for transportation systems of the future.

R&D in the Department of Transportation should be reorganized around clear public interest goals, and Transportation's energy and environmental pursuits should be consonant with DOE's goals. DOT should pursue more multimodal research and system optimization and should increase its focus on developing integrated transit systems with improved efficiency, to reduce urban congestion and enhance air quality. The Automated Highway System research needs to be thoroughly evaluated, key technical assumptions must be

documented and peer-reviewed, and then the program should be reorganized around the public interest goals mentioned above.

Increasing energy efficiency has an extraordinary payoff. It simultaneously saves billions of dollars, reduces oil imports and trade deficits, cuts local and regional air pollution, and cuts emissions of carbon dioxide. DOE research, complemented by sound policy, can help the country increase energy efficiency by a third or more in the next 15 to 20 years.

Fossil-Energy Technology

Fossil fuels supply 85 percent of U.S. energy and 75 percent of all energy globally. They will continue to be essential to the energy economies of the United States and the world well into the twenty-first century. R&D on fossil-fuel technologies is warranted to minimize the costs, impacts, and risks of this continuing reliance on fossil fuels and to exploit the opportunities it represents for U.S. industry and the U.S. economy.

Challenges and Opportunities

DOE Fossil Energy R&D programs are directed — appropriately in the Panel's judgment — at two important challenges: (1) reducing the environmental impacts (including CO_2 emissions) that constrain fossil-fuel use; and (2) reducing the vulnerability of the economy to oil price shocks (caused by excessive dependence on imported oil and potential instabilities in the Middle East) by helping ensure the availability of secure and affordable transportation fuels. In the process, the Department aims to maintain U.S. science and technology leadership in fossil-fuel related fields.

Over the past two decades, enormous progress has been made in reducing the environmental impacts of fossil-fuel use — particularly of coal use in electric power production — in cost-effective ways. This progress has partly been the result of DOE-industry collaborative R&D and the Clean Coal Technology Demonstration Program. DOE seeks to maintain this progress through pursuit of an idea called Vision 21, with the objective of economical coal and gas power and fuels technology with zero-to-small CO_2 emissions and very low emissions of other air pollutants. This is a most ambitious goal, requiring significant breakthroughs to achieve very high efficiencies of conversion to electricity (and fuels) and cost-effective methods for separating and sequestering CO_2.

In the United States, natural gas has become the fuel of choice for new electric generation because of its low cost, small environmental impacts, relatively small scale (yielding versatile siting and quick installation), and rapidly advancing turbine technology, and because of the competitive pressures of electric industry restructuring. This trend to natural gas is likely to continue for several decades and contributes positively to DOE's environmental objective, particularly by reducing CO_2 emissions to the extent that gas replaces coal.

As a consequence, the major markets for advanced coal power and fuels technologies will not be in the United States but in coal-intensive developing countries such as China and India where gas is not widely available for these purposes. Providing attractive coal

technologies that are much more efficient with greatly reduced CO_2 and other emissions contributes to DOE environmental objective. For the United States to take advantage of this environmental opportunity, it must maintain technological leadership in coal-power technologies and develop a strong international program including collaborative R&D, development, and commercialization activities. This will require a paradigm shift away from the current focus on the U.S. market and toward a focus on coal-intensive developing countries.

Relative to the challenge of ensuring secure and affordable transportation fuels, DOE R&D is developing and demonstrating technologies that can enhance domestic oil and gas production, diversify supply, and reduce the cost of converting natural gas (and coal, biomass and waste) to clean fuels for transportation. Activities to enhance production include technology transfer to independent oil and gas producers to help bolster production from mature resources and high risk R&D investments at the front end of the resource cycle for frontier provinces. The potential return to the government from taxes and royalties alone justifies the investment, not to mention reducing balance of payment imbalance and losses to the economy in event of a future oil price shock. It is good insurance both from the point of view of oil dependence and for the climate change issue because of the importance of natural gas as a transition fuel during the next century.

Budget, Goals, and Initiatives

The Panel's analysis of these challenges and opportunities leads us to recommend that the that the Fossil Energy budget remain at about the current level in constant dollars but with a significant reorientation and new initiatives aimed at Vision 21, gas as a transition fuel, and a comprehensive transportation fuel R&D strategy.

Coal and Gas Power and Fuels. The Panel endorses Vision 21 as the long-term objective and recommends reorientation of DOE R&D priorities toward it. This should include continued emphasis to improve efficiency of the combined cycle using high temperature fuel cells, development of advanced gasification technologies (for coal, biomass, or waste) for the flexible production of power and clean transportation liquid fuels (ultimately hydrogen and separated CO_2). It should also include initiating a science-based CO_2 sequestration program in cooperation with the US Geological Survey, industry, and universities, with an annual budget rising to $20 million dollars or more in 2003. Hydrogen may prove to be the transportation fuel of the future if fuel cells become the power source of choice for vehicles, and fossil fuels are the likely least expensive route to hydrogen assuming sequestration is practical.

Phase-Outs. As part of this reorientation, the Panel recommends that the Department terminate: (1) direct liquefaction of coal, because it doesn't fit Vision 21; (2) the solid fuels and feedstocks program, directing the funding instead toward a comprehensive, science-based program to reduce hazardous air emissions from existing and future coal power plants; and (3) the Low Emissions Boiler System program. It should phase out near-term clean-coal programs that do not contribute to Vision 21 or to providing much better low-CO_2-emissions technology choices for developing countries.

Oil and Gas Production and Processing. Because of its importance as a transition fuel for the United States in controlling CO_2 emissions, the Panel recommends more intense effort on natural gas production and processing, including a major initiative for DOE to work with USGS, the Naval Research Lab, Mineral Management Services, and the industry to evaluate the production potential of methane hydrates in US coastal waters and world wide. The resource is very large indeed, in the range of 100,000 to 1,000,000 Tcf (trillion cubic feet). This research might well interface with hydrogen-production and CO_2-sequestration efforts with CO_2 hydrates as the sequestered state of the gas.

Transportation Fuels Strategy. The Panel recommends that DOE develop a comprehensive transportation fuels strategy, beginning with an analysis of the potential for technologies to increase the price elasticity of oil supply and demand including the impact of substitutes. This effort should include, for example, R&D focused on reducing the cost of producing transportation fuels from natural gas and work on indirect liquefaction of coal and biomass. Such an effort is supportive of Vision 21 and may improve its flexibility for combined fuel and power generation, including eventually producing hydrogen for central or distributed use with CO2 sequestering.

Nuclear-Energy Technology

Nuclear energy can be generated by fission (the splitting of a nucleus) or by fusion (the joining of two nuclei). Neither fission nor fusion reactions generate greenhouse gases or the air pollutants that produce urban smogs and regional acid precipitation. Fission power currently provides about 17 percent of the world's electric power, with 442 nuclear power reactors operating in 30 countries and 36 more plants under construction. Fusion power requires much additional work in the quest to make the fusion reaction self-sustaining and to design and build practical fusion power plants; the most optimistic timetable for fusion to reach commercialization is another half century. But the potential benefits of fusion are so large that fusion R&D is an important component of current energy R&D portfolios in the United States and internationally.

Challenges and Opportunities: Fission

Several problems compromise fission's potential as an expandable energy source today and into the future: disposal of spent nuclear fuel; concerns about nuclear weapons proliferation; concerns about the safe operation of plants; and uncompetitive economics. But given the projected growth in global energy demand as developing nations industrialize, and given the desirability of stabilizing and reducing GHG emissions, it is important to establish fission energy as a widely viable and expandable option if this is at all possible. A properly focused R&D effort to address the problems of nuclear-fission power — economics, safety, waste, proliferation — is therefore appropriate. World leadership in nuclear-energy technologies and the underlying science is also vital to the United States from the perspective of national security, international influence, and global stability.

Although the United States has the largest number of operating reactors of any country in the world, the outlook is that no new nuclear plant will be built in this country in the next 10 to 20 years. The decline of nuclear power in the United States has resulted from many factors: a sharp drop in annual electricity consumption growth rates, low gas prices and improved efficiency of gas-fired combined cycle plants, rapid escalation of nuclear plant construction costs, the unresolved problems of waste disposal and storage, and concerns about proliferation and safety. These factors, combined with the upcoming deregulation of the electric utilities, may lead to early shutdown of operating nuclear plants in the United States.

Budget, Goals, and Initiatives: Fission

Based on its analysis of the potential and problems of fission power, the PCAST Energy R&D Panel recommends that nuclear fission R&D be increased from $42 million in FY 1997 to $119 million in FY2003 (as-spent dollars). Included in these totals throughout the period is about $6 million per year for university programs, including fellowships and fuel support for university reactors. The Panel makes the following further observations and recommendations about the fission R&D effort:

Operating Reactors. Extending the operation of nuclear plants will make it easier to meet GHG emission goals. The panel recommends that DOE work with its laboratories and the utility industry to develop a program to address the problems that may prevent continued operation of current plants. We recommend such a program be funded at $10 million per year, to be matched by industry.

Nuclear Energy Research Initiative. DOE should establish a new program — the Nuclear Energy Research Initiative — funded initially at $50 million per year and increasing by FY 2002 to $100 million per year (as-spent dollars), which would competitively select among proposals by researchers from universities, national laboratories, and industry to address key issues affecting the future of fission energy including: proliferation-resistant reactors or fuel cycles; new reactor designs with higher efficiency, lower-cost, and improved safety to compete in the global market; lower-output reactors for use in settings where large reactors are not attractive; and new techniques for on-site and surface storage and for permanent disposal of nuclear waste. This approach is in contrast to the traditional style of directed research by DOE Nuclear Energy program (in which the program office defines the topics, milestones, and scope) and follows instead a model along the lines of the Environmental Management Science Program (EMSP).

Coordination: DOE should improve coordination and integration among the eight DOE program offices sponsoring R&D applicable to fission energy.

Challenges and Opportunities: Fusion

The objective of DOE's fusion energy sciences program is to develop the scientific and technological basis for fusion as a long-term energy option for the United States and the world. The fusion R&D program is strongly centered in basic research and supports the important field of plasma science. Results and techniques from fusion plasma science have had

fundamental and pervasive impact in many other scientific fields, and they have made substantial contributions to industry and manufacturing. Since 1970, fusion power in experiments has increased from less than 0.1 watt to more than 10 megawatts.

The nation's fusion energy research program has received three major reviews since 1990, the most comprehensive being the 1995 study by the PCAST Panel on the U.S. Program of Fusion Energy Research and Development.(PCAST-95). PCAST-95 recommended an annual budget of $320 million. In FY 1996, Congress reduced the fusion budget by about one-third and directed DOE to restructure its fusion energy program. The present funding level of $230 million is too low in the view of the PCAST Energy R&D panel; it allows no significant U.S. activity relating to participation in an international program to develop practical low-activation materials; reduces the level of funding for the design of the International Thermonuclear Experimental Reactor (ITER); forced an early shutdown for the largest U.S. fusion experiment; and canceled the next major U.S. plasma science and fusion experiment. It also limited the resources available to explore alternative fusion concepts.

Budgets, Goals, and Initiatives: Fusion

Based on its analysis of the potential of fusion power and the challenges and opportunities in this field, as just described, the PCAST Energy R&D Panel recommends that fusion R&D funding be increased from its annual level of $232 million in the FY 1997 appropriation to reach $320 million per year by FY2002 (as-spent dollars). This would restore fusion R&D funding to the level
which the 1995 PCAST study of fusion-energy R&D recommended be maintained from FY 1996 onward.

Our Panel reaffirms support also for the specific elements of the 1995 PCAST recommendation that the program's budget-constrained strategy be around three key principles: (1) a strong domestic core program in plasma science and fusion technology; (2) a collaboratively funded international fusion experiment focused on the key next-step scientific issue of ignition and moderately sustained burn; and (3) participation in an international program to develop practical low-activation materials for fusion energy systems. The Panel makes the following further observations about the fusion R&D effort:

International Collaborations. The U.S. program should establish significant collaborations with both the JET program in Europe and the JT-60 program in Japan. Such collaboration should provide experience in experiments that are prototypes for a burning plasma machine, such as ITER, and that can explore driven burning plasma discharges

ITER. The Panel judges that the proposed 3-year transition between completion of the EDA and an international decision to construct is reasonable and that the ITER effort merits continued U.S. involvement. It would be helpful to all parties in the ITER enterprise if at least one of the parties would express, within the next year or two, its intention to offer a specific site for ITER construction by the end of the 3-year period. Clearly, one major hurdle to ITER construction is its total project cost, most recently estimated to be $11.4 billion, with the host party expected to fund a substantial share. If the parties agree to move forward to

construction, the U.S. should be prepared to determine, with stakeholder input, what the level and nature of its involvement should be. The PCAST Energy R&D Panel believes that if no party offers to host ITER in the next three years, it will nonetheless be vital to continue without delay the international pursuit of fusion energy. A more modestly scaled and priced device aimed at a mutually agreed upon set of scientific objectives focused on the key next-step issue of burning plasma physics may make it easier for all parties to come to agreement.

Renewable-Energy Technology

Renewable energy technologies (RETs) can provide electricity, fuels for transport, heat and light for buildings, and power and process heat for industry. These technologies generally have little or no emissions of greenhouse gases (GHGs), air pollutants, or other environmental impacts. RETs can also offset imports of foreign oil and offer important economic benefits; for example growing biomass energy crops on excess agricultural lands would increase farm income while potentially allowing a reduction in Federal farm income support programs.

Challenges and Opportunities

The primary challenge facing RETs today is relatively high unit costs, but remarkable progress has been over the past two decades. Costs of energy from RETs such as wind turbines and photovoltaics (PVs) have come down by as much as 10 times. Much further progress is expected, to the extent that RETs could become major contributors to U.S. and global energy needs over the next several decades. The Shell International Petroleum Company, for example, projects that by 2025 renewable energy sources could contribute to global energy one-half to two-thirds as much as fossil fuels do at present, with new renewable sources (excluding hydropower and traditional biomass) accounting for one-third to one-half of total renewables.

Much of the global market growth for RETs, as well as for total energy, will take place in developing countries. The small scales and modularity of most RETs are well matched to energy technology needs in developing countries. Also, the inherent cleanliness of most RETS will have a special appeal, making it possible to reduce environmental problems without resorting to complex regulatory controls as is done for conventional energy systems.

Budget, Goals, and Initiatives

In light of the remarkable progress already made in many areas of DOE Renewable Energy program, the good prospects for further gains, and the substantial potential impacts renewables could have in addressing the multiple challenges posed by energy system in the United States and worldwide, the PCAST Energy R&D Panel believes that the Renewable Energy R&D Program should be substantially expanded, from annual spending of $270 million in FY 1997 to a level of about $650 million in 2003 (as-spent dollars), with goals that include the following:

Wind. Reduce by 2005 wind electricity costs to half of today's costs, so that wind power can be widely competitive with fossil-fuel-based electricity in a restructured electric industry, through R&D on a variety of advanced wind turbine concepts and manufacturing technologies.

Photovoltaics (PV): Pursue R&D that would lead to PV systems prices falling from the present price of $6,000/kW to $3,000/kW in 5 years, to $1500/kW by 2010, and to $1,000/kW by 2020. R&D activities should include assisting industry in developing manufacturing technologies, giving greater attention to balance of system issues, and expanding fundamental research on advanced materials.

Solar Thermal Electric Systems. Strengthen ongoing R&D for parabolic dish and heliostat/central receiver technology with high temperature thermal storage, and develop high temperature receivers combined with gas-turbine based power cycles; goals should be to make solar-only power (including baseload solar power) widely competitive with fossil fuel power by 2015.

Biopower. Enable commercialization, within ten years, of advanced energy-efficient power-generating technologies that employ gas turbines and fuel cells integrated with biomass gasifiers, building on past and ongoing R&D for coal in such configurations, and exploiting the advantages of biomass over coal as a feedstock for gasification. These technologies could be widely competitive in many developing country markets and in U.S. markets that use biomass residues or use energy crops in systems that derive coproducts from biomass.

Geothermal Energy. Continue work on hydrothermal systems, and reactivate R&D on advanced concepts, giving top priority to high-grade hot dry-rock geothermal; this technology offers the long-term potential, with advanced drilling and reservoir exploitation technology, of providing heat and baseload electricity in most areas.

Biofuels. Accelerate core R&D on advanced enzymatic hydrolysis technology for making ethanol from cellulosic feedstocks, with the goal that between 2010 and 2015 ethanol produced from energy crops would be fully competitive with gasoline as a neat fuel, in either internal combustion engine or fuel cell vehicles; coordinate this development with the biopower program so as to co-optimize the production of ethanol from the carbohydrate fractions of the biomass and electricity from the lignin using advanced biopower technology.

Hydrogen. Carry out R&D on hydrogen using and producing technologies; coordinate hydrogen-using technology development with proton-exchange-membrane fuel-cell vehicle development activities in the Department's Energy Efficiency program. Give priority in hydrogen-production R&D to co-optimizing the production of hydrogen from fossil fuels and sequestration of the CO_2 separated out during the production process, in collaboration with the Fossil Energy program.

Hydropower. To sustain and increase over 92,000 MWe of hydro capacity, additional R&D is needed to provide a new generation of turbine technologies that are less damaging to fish and aquatic ecosystems. By deploying such technologies at existing dams and in new low-

head, run-of-river applications, as much as an additional 50,000 MWe could be possible by 2030.

Crosscutting and other programs. Crosscutting programs that should be strongly supported include Resource Assessment, International Programs, and Analysis. In addition, R&D is needed energy storage, electric sytems, and systems integration.

Further Findings and Recommendations

The Panel believes that there are good prospects that these goals can be realized with the combination of an expanded R&D effort and appropriate demonstration and commercialization initiatives. DOE program has demonstrated remarkable gains in technology performance and cost reductions and has laid the foundation for large further gains. The R&D effort should be intense over the course of the next decade, with much more emphasis than at present in DOE program on both core applied research and development and fundamental research directed to serving needs identified in the programs.

For technologies that continue to show promise, R&D budgets should be sustained at the elevated levels for several years (the number varying with the technology) until the technologies become established in the market, the industry has sufficient revenues from these RET markets to shoulder a greater share of needed continuing R&D, and government's role can be reduced to supporting mainly long-term R&D. For both wind power and biopower most of the principal R&D goals could be met in a decade or less; for these technologies Federal R&D budget support could thereafter begin to decline. For other technologies it will take longer, but in nearly all cases principal program goals should be achievable in less than 20 years.

Cross-Cutting Issues

In what follows we elaborate briefly our findings and recommendations relating to four sets of issues that cut-across the applied energy-technology R&D programs discussed above: the relation of DOE's Basic Energy Sciences program to applied energy-technology R&D, analysis of the portfolio as a whole and the leverage it offers against the energy challenges faced by the nation and the world; considerations related to commercialization of the fruits of R&D; and certain international aspects of R&D.

Links Between Applied Energy Technology R&D and Basic Energy Sciences

The Panel's review of DOE energy R&D activities identified many areas where technological advance could be accelerated if more attention were given to fundamental questions identified in these programs. Examples include better understanding of reactions at the interface of electrodes and electrolytes in fuel cells, the capacity of carbon nanostructures for hydrogen storage, the chemistry and fluid dynamics of CO_2 storage in saline aquifers, the physics of thin-film photovoltaic materials, and many others. The Panel found that linkages between the Basic Energy Sciences (BES) programs (where such issues are investigated) and the applied energy-

technology programs (where the findings could be put to use) need to be strengthened in many cases.

While the technology programs do benefit today from the growing body of fundamental knowledge being generated under BES programs, they would benefit much more if BES were to address specific questions identified as important in these programs. The Panel recommends that BES allocate additional resources to support fundamental research activities addressing needs of the technology programs. This could be facilitated by mechanisms such as co-management and co-funding with — or budget sign-off by, or re-routing budgets through — the applied energy-technology programs.

Our recommendation that BES direct some of its resources to serving these needs might raise concerns that the creativity of basic science will be lost if it is constrained by premature thought of practical use, and that applied research invariably drives out pure, if the two are mixed. What is being sought here, however, is not to redirect BES resources to applied research. The technology programs support applied research but give little attention to addressing fundamental questions such as the above. The net effect of this recommendation should be to expand, not diminish, the portfolio of fundamental research activities within the limits of overall budget constraints. In light of the growing interest among policy planners in harnessing science for the technological race in the global economy, the allocation of some BES resources to the development of fundamental research programs that would serve the energy technology programs should add to the political appeal of supporting basic research generally.

Portfolio Analysis and Leverage

Developing the appropriate degree of diversity and balance in the Department's overall energy R&D portfolio is difficult. Technologies have many different attributes — cost (of the R&D to develop them and of the technologies themselves, once they are developed), performance, risk, return, potential contributions over time to energy and environmental goals, and others. How can one fairly evaluate the many R&D alternatives and select an R&D portfolio that best meets our national goals and needs? No single quantitative measure can encompass the range of relevant attributes. One technology may have substantial environmental benefits, a second may contribute more to national security, a third may have only modest benefits but have low risks and costs to develop.

The Panel has worked hard at exploiting and refining various ways to portray the diverse characteristics of different energy options in a way that facilitates comparisons and the development of an appropriate portfolio balance in light of the challenges facing energy R&D and in light of the nature of private-sector and international efforts and the interaction of U.S. government R&D with them. We have made some progress, but a much larger and continuing effort in this direction by the Department of Energy itself is called for. (In saying this we echo one of the strongest recommendations of the 1995 Secretary of Energy Advisory Board report on Strategic Energy R&D — a recommendation that alas has so far borne little fruit.) Such analyses should be done on a regular basis as national needs and R&D options and opportunities change. We recommend that DOE regularly and systematically conduct — with external peer review — a portfolio analysis across the breadth of R&D options and to use this as an input to overall program planning.

The potential overall impact of the sector-by-sector energy R&D portfolio developed by the Panel can be illustrated by some simple "back-of-the-envelope" analyses. Examples for oil imports and carbon emissions are schematically shown in figures ES-1 and ES-2; details of these highly simplified projections are provided in Chapter 7. For clarity, only a few, highly aggregated sets of technologies are shown.

Consider oil imports. Under "business-as-usual conditions, U.S. oil imports could increase from 8.5 million barrels per day at a cost of $64 billion dollars in 1996 to nearly 16 million barrels per day at a cost of $120 billion (assuming $20 dollars per barrel) in 2030. With continued R&D to increase domestic production from marginal oil supplies, an aggressive ethanol program (based on cellulosic biomass, not corn), and rapid development and penetration of the market by PNGV and light- and heavy-duty truck technologies, we estimate that this import could be reduced to something on the order of 6 million barrels per day oil import demand in 2030, as illustrated in figure ES-1. Estimates of this sort are necessarily highly approximate, since they depend not only on the somewhat unpredictable pace of R&D successes but also future market conditions and measures taken to speed market penetration under whatever those conditions are; nonetheless, such "ballpark" estimates give at least a rough indication of the magnitude of the challenge the nation faces and and size of the opportunity to address it with the stronger R&D program outlined here.

Potential impact on carbon dioxide emissions (customarily measured in tons of carbon contained in the emitted CO_2) is clearly also a crucial element of a portfolio's leverage against the energy-related challenges of the next century. Figure ES-2 illustrates, in a highly stylized and schematic way, how the factors most germane to an analysis of leverage against CO_2 emissions can be portrayed in a single diagram: the length of time until a new technology is ready to begin penetrating the market, the cost of the R&D effort needed to get to that point, and the rate at which the technology could penetrate the market (reflected in the diagram as the rate of increase in avoided CO_2 emissions) after that time. (With some modification such a diagram could also show the effect, on the potential for emissions avoidance, of the different sizes of the various energy-supply or end-use markets being penetrated.)

The Panel has not been able, in the time available for this study, to complete the sorts of analyses that would be necessary to specify the relevant market-entry points, associated research investments, and plausible penetration rates — and the uncertainty ranges associated with all of these — with any confidence. Figure ES-2 is based on very approximate understandings of needed research investments and market-entry points developed in the course of our study, and on crude guesses about penetration rates (which were uniform across the technologies shown, in the absence of the sort of analysis that would be required to do this in a differentiated way). What can be said in favor of this very rough and preliminary depiction of potential leverage is that (a) it illustrates what we believe DOE should be doing in the way of portfolio analysis, with a much larger analytical effort behind it than they or we have mustered until now, and (b) the timing and magnitudes of the conceivably achievable avoided carbon emissions shown in the diagram are roughly consistent with what other major recent studies of the potential of new technologies for this purpose have found.

Our Figure ES-2 shows only technologies that would not begin penetrating markets until after 2010. They offer large emissions-avoidance potential, but only well into the next century. (Of course, the point of increasing R&D investments in appropriately targeted areas is to move forward the date at which such technologies can begin penetrating their markets.) Options that could have an impact by 2010 are not shown here but have been separately examined by DOE in a recently released report; these earlier-impacting options necessarily depend largely on R&D that has already been done.

Commercialization Considerations

To achieve the sorts of impacts illustrated schematically in Figures ES-1 and ES-2 would require more than R&D in many cases.. New technologies face the chicken-and-egg problem of generally having high costs, and thus being limited to low market volumes, but needing large market volumes to drive costs down. Making this transition is difficult given the low costs of energy today and given that the public benefits of new energy technologies — notably environmental quality and national security — are generally not valued in the market. Industry-led, public-private collaborations in demonstration and commercialization of new energy technologies can be an appropriate way to address this difficulty in ways that ensure that R&D programs are appropriately targeted and market relevant and that the benefits of the public investment in R&D are realized in market penetration rates commensurate with the sum of the private and public benefits of such penetration.

After consideration of the market circumstances and public benefits associated with the energy-technology options for which we have recommended increased R&D, the Panel recommends that the nation adopt a commercialization strategy in specific areas complementing its public investments in R&D. This strategy should be designed to reduce the prices of the targetted technologies to competitive levels, and it should be limited in cost and duration. The Panel does not make a recommendation as to the source of funds for such an initiative. We do believe, however, that such a commercialization effort should be designed to be very efficient in allocating funds to drive prices down, minimally disruptive of energy/financial systems, and temporary.

International Aspects

Markets for many new energy supply technologies will be very limited in the United States for the next decade or two due to slow growth in demand and the availability of low cost natural gas; most of the growth in world energy production and use and in carbon emissions will take place in developing countries. For the United States to maintain scientific, technological, and market leadership in these critical energy technologies, it will be essential for public R&D and development and commercialization programs to broaden their scope to directly address international energy issues, including both collaborative R&D and market competition. This can provide us as well as our partners substantial economic and environmental benefits.

The Panel recommends that the government and government/national-laboratory/industry/university consortia should engage strongly in international energy

technology R&D and development and commercialization efforts to regain and/or maintain the scientific, technical, and market leadership of the United States in energy technology. This should include increased R&D — particularly in collaboration with developing countries, temporary support for D&C activities where appropriate — and responses to foreign export promotion activities where necessary.

DOE Management of Its Energy R&D Programs

The necessity of linking fundamental research with applied R&D and with development and commercialization, the increasing complexity of R&D efforts, globalization of R&D and technology markets, heightened global market competition, and other evolving factors in the energy field have several important implications for energy R&D management. The complexity and technical demands of R&D require increased industry/national-lab/university peer review and technical oversight and direction of R&D programs. Linkages require improved coordination.

Better communications can enable reduced administrative procedures and management overheads, and can improve coordination by pushing these responsibilities down to the operational level. Efficient use of resources requires careful establishment of R&D targets and timelines, and ongoing measurement of progress. Although DOE has been making some efforts in these areas and some programs are beginning to establish effective models that can be applied more broadly, in general these factors need to be better addressed in DOE energy R&D management.

To address these management issues, and above all to increase the efficiency with which public dollars invested in energy R&D yield the results that the national interest requires, the Panel offers the following specific recommendations:

(1) Overall responsibility for DOE energy R&D portfolio should be assigned to a single person reporting directly to the Secretary of Energy; similarly, a single individual should be given the responsibility and authority for coordination of cross-cutting programs between the applied-technology programs, reporting to the single person responsible for the overall R&D portfolio.

(2) Industry/national-laboratory/university technical oversight committees should work with DOE to provide overall direction to energy R&D programs, with DOE facilitating and administering the process;

(3) All R&D programs should undergo outside technical peer review every 1-2 years, but interim internal process-oriented reviews should be reduced to a minimum.

(4) DOE Staff technical skills should be strengthened by training, targeted hiring, and by systematically rotating external technical (and managerial) staff through DOE as senior professionals with significant responsibilities for all aspects of program management.

(5) Lead laboratories should be named and laboratories should be treated by DOE as integrated entities, not as collections of projects independently controlled from DOE headquarters.

(6) Industry/laboratory/university partnerships should conduct the energy R&D that is funded by DOE, in most cases.

(7) The national laboratories should be encouraged to perform work for clients other than DOE, inside and outside the government, as appropriate, and processes for doing this should be streamlined.

(8) DOE staff procedures for energy technology programs should be reviewed in detail, and staff levels adjusted accordingly.

CONCLUDING OBSERVATIONS AND ONE MORE RECOMMENDATION

Funding and managing the energy R&D needed to help address the energy challenges and opportunities of the next century are tasks not for the Federal government alone but for all levels of government, for industry, for universities, for the nonprofit sector, and for a wide variety of kinds of partnerships among entities in these different categories. The Panel's charge was to review Federal energy R&D, but we have been attentive to the ways in which the role of the government relates to and interacts with the roles of the other sectors. Our recommendations aim to focus the government's resources on R&D where high potential payoffs for society as a whole justify bigger R&D investments than industry would be likely to make on the basis of its expected private returns, and where modest government investments can effectively complement, leverage, or catalyze work in the private sector.

The funding increases we are proposing for Federal energy R&D, in order to better match the energy R&D portfolio of the public and private sectors combined to the energy-related challenges and opportunities facing the nation, appear quite large when expressed as percentage increases in some of the particular DOE programs that would be affected. But the increase in annual spending — amounting altogether to an extra billion dollars in 2003, compared to that in 1997, for R&D on all the applied energy-technology programs together — is equal to less than a fifth of one percent of the sum that U.S. firms and consumers spent on energy in 1996; and it would only bring the Department of Energy's spending on applied energy-technology R&D back to where it was in 1992, in real terms. The potential returns to society from this modest investment are very large. They can be measured in energy costs lower than they would otherwise be, oil imports smaller than they would otherwise be, air cleaner than it would otherwise be, more diverse and more cost-effective options for reducing the risk of global climate change than we would otherwise have, and much more.

If this is such a good case, why hasn't it been made and accepted before now? Actually the case has been made often before, by energy experts and by studies like this one. It has not been entirely heeded for a variety of reasons, most of them discussed above and many of them perfectly understandable. But perhaps the most important reason that the government today is not doing all that it should in energy R&D is that the public has been lulled into a sense of complacency by a combination of low energy prices and little sense of the connection between

energy and the larger economic, environmental, and security issues that people *do* care very much about. In a way the low priority given to energy matters is reflected even in the Department of Energy itself, where energy is only a modest part of the Department's array of missions and there is no official responsible for all of the Department's energy activities and those alone.

What we have here is therefore, in part, an education problem. There needs to be more public discussion and a growing public understanding of why energy itself — and therefore energy R&D — is important to the well-being of our nation and the world. In this the scientific and technological community has an obvious role to play, and we hope this report will be seen as a positive contribution to that. But the Federal government, led by the President, also has an important educational role to play, reflected in what is said and in what is done. As the last of the recommendations in this report, which was commissioned by the President, we therefore offer the following:

> We believe the President should increase his efforts to communicate clearly to the public the importance of energy and of energy R&D to the nation's future, and that he should clearly designate the Secretary of Energy as the national leader and coordinator for developing and carrying out a sensible national energy strategy, which of course includes not only energy R&D but much else.

* * * * *

Table ES-3. **Recommended DOE Applied Energy-Technology (ET) R&D Initiatives and Budget Authority** (in millions of as-spent dollars)

PROGRAM[a]	R&D Activities, Initiatives, and Budget Changes	FY 1997	FY 1998	FY 1999	FY 2000	FY 2001	FY 2002	FY 2003
Efficiency: Buildings	Building System Design and Operation: advanced sensors; smart controls; automated diagnostics; and whole-building optimization and design tools.	24	33	38	48	60	72	84
	Building Equipment and Materials: advanced materials; advanced energy-efficient HVAC, lighting, windows, appliances, office equipment, etc.; and insulation initiative.	27	37	57	72	85	98	111
	Codes and Standards: for efficient appliances and buildings; technical assistance.	12	21	25	25	25	25	25
	Crosscutting Activities: technology roadmapping and partnership development with industry following the model of the DOE Industries of the Future program.	--	--	20	25	30	35	35
	Other: management and planning, and other activities.	19	20	20	20	20	20	20
	Subtotal	81	111	160	190	220	250	275
Efficiency: Industry	Industries of the Future: advanced technologies for energy intensive industries—aluminum, cement, chemicals, forest products, glass, metal casting, refining, steel, agriculture—and for emerging energy-intensive industries following technology roadmaps.	46	56	65	75	85	95	110
	Crosscutting Activities: advanced microturbines (40-200 kW), sensors, motor drive systems, and materials; work with DOE/OUT on biomass Integrated Gasification Combined Cycle.	38	38	70	80	90	95	100
	Technology Access: innovation grants; industrial assessments, "Climate Wise", and motors.	25	37	40	40	45	45	50
	Other: management and planning, and other activities	7	8	10	10	10	10	10
	Subtotal	116	139	185	205	230	245	270
Efficiency: Transport	PNGV: better emissions controls for light diesels; hybrid vehicles; and system integration.	105	129	100	100	100	100	75
	PNGV II: fuel cells, microturbines, advanced energy storage, system integration.	--	--	75	85	100	100	125
	Advanced Heavy Vehicles: efficient diesels, diesel pollution reduction, and hybrids.	20	18	30	40	50	55	60
	Advanced Materials: high-temperature/high-strength materials to reduce weight 25%.	33	31	35	40	40	40	45
	Technology Deployment: clean cities program, alternative fuel vehicles, and other activities.	11	17	20	20	20	20	20
	Other: management and planning, and other activities	7	9	10	10	10	10	10
	Subtotal	176	204	270	295	320	325	335
Fossil Energy	Coal Power: end Low Emission Boiler System, phase out near-term clean coal activities, accelerate R&D on advanced power systems.	86	84	79	90	87	88	82
	Coal Fuels: end direct liquefaction and solid fuels and feedstocks R&D; develop science-based hazardous air emissions program.	16	16	9	12	15	16	16
	Gas Power: strengthen solid-oxide fuel-cell R&D and other advanced research.	97	78	92	92	83	74	70
	Oil and Gas Production and Processing: maintain oil programs for marginal resources; strengthen gas production and processing R&D; and increase advanced research.	70	77	86	94	107	110	113
	Carbon Sequestration: strengthen science-based carbon sequestration program.	1	2	10	11	17	23	22
	Methane Hydrates: develop science-based program with industry, Federal agencies, and the Navy to understand the potential of methane hydrates worldwide	0	0	5	5	11	11	12
	Hydrogen Manufacture/Infrastructure: conduct R&D on hydrogen production from fossil fuels	0	0	1	2	6	6	7
	Technology/Oil Price Elasticities: analyze technologies to reduce cost of oil shocks.	0	0	1	1	1	1	0
	Developing-Country Technologies: conduct collaborative R&D with other countries.	0	0	1	2	6	6	6
	Other: management and planning; environmental restoration; cooperative R&D, etc.	95	89	95	97	100	102	105
	Subtotal	365	346	379	406	433	437	433

N[redacted] Fission	Operating Reactors: R&D to address problems that [redacted]event continued operation of existing reactors.	4	25	10	10	10	[redacted]	10
	Nuclear Energy Research Initiative: competitively select among proposals by researchers from universities, national laboratories, and industry that address issues including proliferation-resistant reactors or fuel cycles, new reactor designs with higher efficiency, lower cost, and improved safety; low-power reactors; and new techniques for on-site and surface storage and for permanent disposal of nuclear waste	0	0	50	70	85	100	103
	Education: university research reactors and other support	4	6	6	6	6	6	6
	Other: advanced light water reactor and reactor concepts	34	15	0	0	0	0	0
	Subtotal	42	46	66	86	101	116	119
Nuclear Fusion	Plasma Science: conduct research on fundamental plasma science; develop fusion science and technology and plasma confinement innovations; and pursue fusion energy science and technology as a partner in international efforts.							
	Subtotal	232	225	250	270	290	320	328
Renewable Energy	Biomass Fuels: strengthen feedstock development; advance enzymatic hydrolysis and other conversion technologies in integrated power and fuel systems.	28	38	58	76	94	97	99
	Biomass Power: develop biomass materials handling equipment; integrated gasification combined cycles; biogasification-fuel cell systems; and small gasification-engine systems.	28	38	63	86	89	91	93
	Geothermal: strengthen hydrothermal research; reactivate R&D on advanced resources; expand advanced drilling R&D; and increase R&D on reservoir testing and modeling.	30	30	42	49	50	51	52
	Hydrogen: reorient near-term demonstrations and launch initiative with DOE Fossil Energy on innovative hydrogen production from fossil fuels with sequestration.	15	15	16	16	17	17	17
	Hydropower: develop "fish-friendly" turbines and low-head run-of-river turbines; analyze coupling of hydropower to intermittent renewables.	1	1	4	8	11	11	12
	Photovoltaics: accelerate basic PV science; develop laboratory scaleup to first-time manufacturing; and support engineering science for large-volume, low-cost production.	60	77	105	130	133	137	140
	Solar-Thermal: strengthen power tower and dish-stirling, esp. optical materials and solar manufacturing initiative; launch initiative on advanced high-temperature receivers.	22	20	32	43	44	46	47
	Wind: accelerate R&D on lightweight adaptive systems, direct-drive variable speed generators, hybrid systems, system integration—including with storage; wind technology manufacturing initiative; fundamental work on materials, and computational aerodynamics.	29	43	53	65	66	68	70
	Systems and Storage: energy storage, esp.. for system integration with intermittents.	32	46	51	54	55	57	58
	Solar Buildings: R&D in efficient and passive whole building design and design tools; building integrated PVs and thermal systems; and initiative on low cost solar water heaters and others.	3	4	6	9	9	9	9
	International: applications-specific systems integration and development, and field studies; collaborative R&D and training; technical assistance; technical/policy analysis.	1	7	11	13	13	14	14
	Resource Assessment: integrated assessments across all resources; further development of geographic information systems; and collaborative R&D with developing nations.	0	0	5	5	6	6	6
	Analysis: systematic analyses of technologies, system integration, markets, and policies.	0	0	4	5	6	6	6
	Other: management and planning; renewable energy production incentive, other.	21	26	25	26	27	26	29
	Subtotal	270	345	475	585	620	636	652
SUBTOTAL		1282	1416	1785	2037	2214	2329	2412

[a]Activities should be done through various partnerships between industry, national laboratories, universities, and Federal/state agencies, as appropriate.

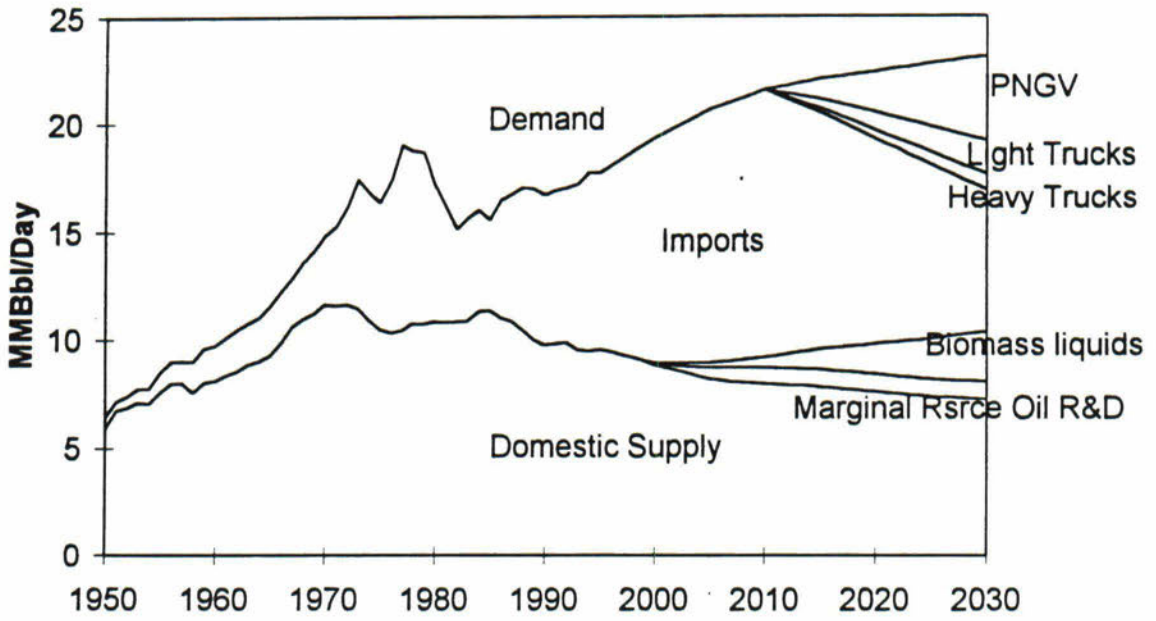


Figure ES-1. Potential Reduction of U.S. Oil Imports by Selected Advanced Technologies.

Historical data and baseline projections from Energy Information Administration (EIA). Vehicle efficiency improvements assume R&D completed by 2004 and commercial production is underway by 2010, with straight-line penetration to 100% of the market by 2030. Improvements entail roughly 60% reductions in fuel intensity for cars and light trucks, 40% for heavy trucks. Contributions from R&D to exploit marginal domestic resources are based on DOE projections. Biomass liquids estimate is based on an aggressive program to produce ethanol from cellulosic biomass. Many other technological possibilities are not shown.

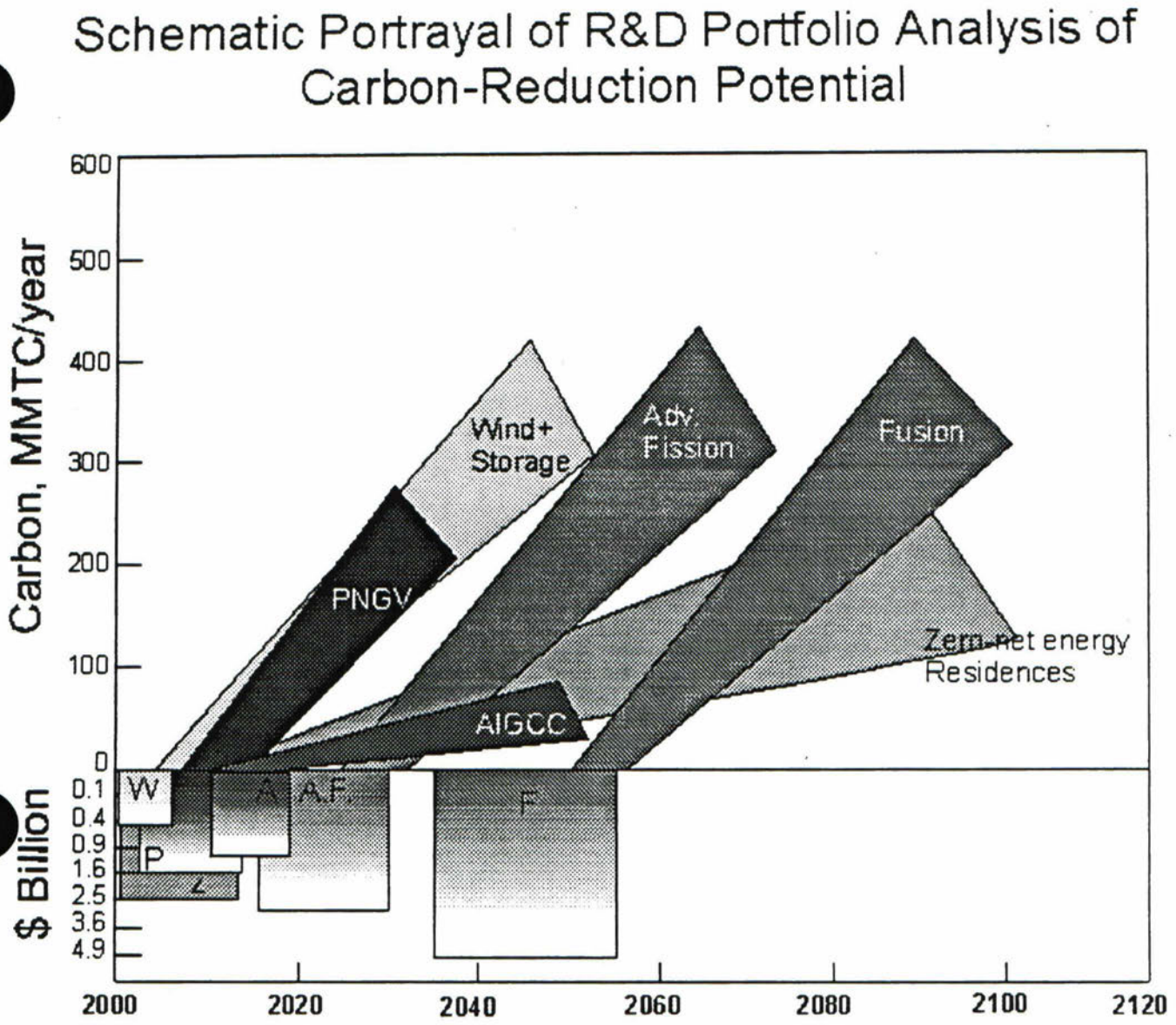


Figure ES-2. Schematic Portrayal of R&D Portfolio Analysis of Carbon-Reduction Potential.

This drawing depicts an approximate range of times when a technology might be available for commercial use—where the shaded wedges touch the time-axis; the potential carbon savings as the technology penetrates the market—depicted by the shaded wedges indicating a range of penetration rates; and the approximate cost of the R&D to develop these technologies to commercialization—depicted by the squares at the bottom of the drawing, which have areas proportional to the discounted present value of the R&D costs. The width of the wedges and shading in the boxes depict uncertainty in these estimates. Maximum slopes of penetration-rate wedges are based on 100% capture of the market for new units and specified turnover times for old units: 15 years for cars, 40 years for electric power plants, 80 years for residential buildings. For simplicity, carbon intensities of the various sectors are assumed to be frozen at 1995 levels. Funding estimates are for applied technology development only; they do not include fundamental science research. Funding for buildings includes commercial buildings, for which carbon savings are not shown. Large, long-term R&D programs assume international collaborations. With refinement and more nuanced analysis behind it, such an approach to illustrating the leverage of an R&D portfolio versus time and investment could be very informative.

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Divider Title: **10**

SCENARIOS OF U.S. CARBON REDUCTIONS

Potential Impacts of Energy Technologies by 2010 and Beyond

Prepared by the
Interlaboratory Working Group on
Energy-Efficient and Low-Carbon Technologies

Oak Ridge National Laboratory*
Lawrence Berkeley National Laboratory*
Pacific Northwest National Laboratory
National Renewable Energy Laboratory
Argonne National Laboratory

Prepared for
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

*Coordinating laboratories for this study

EXECUTIVE SUMMARY

This report presents the results of a study conducted by five U.S. Department of Energy national laboratories that quantifies the potential for energy-efficient and low-carbon technologies to reduce carbon emissions in the United States.[1] The study documents in detail how four key sectors of the economy – buildings, transportation, industry, and electric utilities – could respond to directed programs and policies to expand adoption of energy-efficiency and low-carbon technologies, an increase in the relative price of carbon-based fuels by $25 or $50/tonne (e.g., as a result of a cap on domestic carbon emissions and a market for carbon "permits"), and an aggressive program of targeted research and development. Current projections suggest that a carbon emissions reduction of 390 million metric tons per year (MtC/year) is required to stabilize U.S. emissions in 2010 at 1990 levels.

The study, which has been peer-reviewed by industry and academic experts, uses a technology-by-technology assessment as well as an engineering-economic modeling approach. It draws upon a wide variety of technology cost and performance information to assess potential impacts. Analysis of the buildings, industry, and transportation sectors quantifies the impacts of end-use energy-efficiency improvements on carbon emissions. The utility sector analysis estimates the impacts of those improvements on utility carbon emissions, and quantifies additional emissions reductions through conversion of a number of coal power plants to natural gas, dispatching of the utility grid with $25 and $50/tonne carbon permit prices, the accelerated use of biomass cofiring and wind energy, and other low-carbon electricity supply options. Finally, a number of other promising low-carbon technologies are examined to determine their potential for reducing emissions in the end-use sectors, including advanced gas turbines in industry, transportation biofuels, and fuel cells in buildings.

Three overarching conclusions emerge from the analysis of alternative carbon scenarios. First, a vigorous national commitment to develop and deploy energy-efficient and low-carbon technologies has the potential to restrain the growth in U.S. energy consumption and carbon emissions such that levels in 2010 are close to those in 1997 (for energy) and 1990 (for carbon). We analyze a case in which energy efficiency can reduce carbon emissions by 120 MtC/year by 2010. We analyze a second case, with policies that promote adoption of energy-efficient and low carbon technologies and a $25/tonne carbon permit price, with emission reductions of 230 MtC/year in 2010. Under a $50/tonne carbon permit price and aggresive policies, 2010 emissions could be cut by about 390 MtC/year. The analysis also suggests that substantial additional savings are available if permit prices were to begin to rise above the $50/tonne level.

The second conclusion is that, if feasible ways are found to implement the carbon reductions as described above, all the cases (with reductions varying between 120 and 390 MtC/year by 2010) can produce energy savings that are roughly equal to or exceed costs.[2] The analysis includes only technologies estimated to be cost-effective under 2010 energy prices (with a $25/tonne and $50/tonne carbon permit price for the respective cases); it has not, however, analyzed specific policies to achieve the cases, identified the political feasibility of policies, or described a pathway to achieve the cases.

The third conclusion is that a next generation of energy-efficient and low-carbon technologies promises to enable the continuation of an aggressive pace of carbon reductions over the next quarter century. This report documents a wide array of advanced technology options that could be cost-competitive by the year 2020, assuming a vigorous and sustained program of energy R&D beginning now and extending beyond 2010.

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[1] The five national laboratories participating in the study were: Argonne National Laboratory (ANL), Lawrence Berkeley National Laboratory (LBNL), National Renewable Energy Laboratory (NREL), Oak Ridge National Laboratory (ORNL), and Pacific Northwest National Laboratory (PNNL). LBNL and ORNL were the co-leaders of the effort.

[2] Here we count as benefits only the energy savings to the nation. We have not credited reduced CO_2 emissions or other external benefits. Costs include the increased technology cost plus an approximate estimate of the costs of program and policy implementation.

AUTHORSHIP

Marilyn A. Brown (Oak Ridge National Laboratory) and Mark D. Levine (Lawrence Berkeley National Laboratory) were responsible for the overall leadership of the project. They jointly authored the Executive Summary, Chapter 1 (Analysis Results), and Chapter 2 (Introduction and Background).

Chapter 3 (Buildings) authorship is best described in terms of the analysis for 2010 (Sections 3.2 and 3.3 and associated appendices) and R&D potential in 2020 (Section 3.4). Jonathan Koomey (Lawrence Berkeley National Laboratory) was the lead author for the 2010 analysis. Nathan Martin, Lynn Price, and Mark Levine (LBNL) were co-authors. Marilyn Brown was the lead author for the R&D section, with support from staff at Oak Ridge National Laboratory and Lawrence Berkeley National Laboratory.

Gale Boyd (Argonne National Laboratory), Joseph M. Roop, and Madeline G. Woodruff (Pacific Northwest National Laboratory) were the lead authors of Chapter 4 (Industry) with the exception of Section 4.3 (Low-Carbon Technologies), which was prepared by Helena Chum and Ralph P. Overend (National Renewable Energy Laboratory), Tony Schaffhauser and Marilyn Brown (Oak Ridge National Laboratory), and Tina Kaarsberg (Vista Technologies).

David Greene (Oak Ridge National Laboratory) and Steve Plotkin (Argonne National Laboratory) were responsible for Chapter 5 (Transportation).

Stanton Hadley and Eric Hirst (Oak Ridge National Laboratory) were the authors of Chapter 6 (The Electricity Sector's Response to End-Use Efficiency Changes).

Chapter 7, Electricity Supply Technologies, consists of a variety of topics: Conversion of Coal-Based Power Plants to Natural Gas (Section 7.2) was prepared by David South and Jack Siegel (Energy Resources, Inc.); Renewable Electricity Technologies (Section 7.3) was written by Eldon Boes and Erik Ness with contributions from National Renewable Energy Laboratory staff; the section on Advanced Coal Technologies (Section 7.6) was written by Stanton Hadley (Oak Ridge National Laboratory); and the sections on Efficiency Improvements in Generation and T&D (Section 7.4) and Nuclear Plant Life Extension (Section 7.5) were written by Marilyn Brown (Oak Ridge National Laboratory). Other sections of this chapter are summaries of published materials.

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The completion of this study was guided by a committee of experts from industry, universities, and utility research organizations. The committee was chaired by Bill Fulkerson (University of Tennessee) and included: Morton H. Blatt (Electric Power Research Institute), Daniel E. Steinmeyer (Monsanto Chemical Company), Robert A. Frosch (Kennedy School, Harvard University), Douglas C. Bauer (National Academy of Sciences), Hillard G. Huntington (Energy Modeling Forum, Stanford University) and Thomas Roose (Gas Research Institute).

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Chapter 3 (Buildings): George Courville, Mike MacDonald, Jeff Muhs, John Tomlinson, Jim Van Coevering, Robert Wendt (ORNL); Steve Selkowitz, Joe Huang and Steve Johnson (LBNL).

Chapter 4 (Industry): Jim Chang, Hann Huang, Zhuoxiong Mao, John Molburg, Ken Natesan, Leslie Nieves, and Mike Petrick (ANL), Scott L. Freeman, Gary B. Josephson, and Mark J. Niefer (PNNL), Wayne Hayden (ORNL), Keith Davidson and Bill Major (OnSite Energy, Inc.), and Nancy Margolis (Energetics, Inc.).

Chapter 5 (Transportation): K. G. Duleep (Energy and Environmental Analysis, Inc.).

Chapter 7 (Electricity Supply Technologies): Helena Chum, David Kline and Ralph P. Overend (NREL), Jack Siegel (Energy Resources International, Inc.), Claud Pugh and Mike Sale (ORNL). Ronald Wolk contributed to Appendix G-1 and Ronald Fisher contributed to Appendix G-4.

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Non-participating DOE laboratories were asked to comment on various draft materials. This group of reviewers included Jerome LaMontagne (Brookhaven National Laboratory) and Dan Arvizu (Sandia National Laboratory). Additional valuable comments on earlier drafts of this report were received from John Sheffield (ORNL), Jay Braitsch and Doug Carter (DOE's Office of Fossil Energy), and several staff of the American Council for an Energy-Efficient Economy. Economists Al Link (University of North Carolina at Greensboro) and Stephen DeCanio (University of California at Santa Barbara) also provided review comments on the report.

By acknowledging the involvement of the above individuals and the extensive review process in which they participated, we do not mean to imply their endorsement of the report. Final responsibility for the content of this report lies solely with the authors.

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Chapter 1

ANALYSIS RESULTS

This report presents the results of a study conducted by five U.S. Department of Energy national laboratories that quantifies the potential for energy-efficient and low-carbon technologies to reduce carbon emissions in the United States.[1] The stimulus for this study derives from a growing recognition that any national effort to reduce the growth of greenhouse gas emissions must consider ways of increasing the productivity of energy use. To add greater definition to this view, we quantify the reductions in carbon emissions that can be attained through the improved performance and increased penetration of efficient and low-carbon technologies by the year 2010. We also take a longer-term perspective by characterizing the potential for future research and development to produce further carbon reductions over the next quarter century. As such, this report makes a strong case for the value of energy technology research, development, demonstration, and diffusion as a public response to global climate change.

Three overarching conclusions emerge from our analysis of alternative carbon reduction scenarios. First, a vigorous national commitment to develop and deploy cost-effective energy-efficient and low-carbon technologies could reverse the trend toward increasing carbon emissions. Along with utility sector investments, such a commitment could halt the growth in U.S. energy consumption and carbon emissions so that levels in 2010 are close to those in 1997 (for energy) and in 1990 (for carbon). It must be noted that such a vigorous national commitment would have to go far beyond current efforts. Second, if feasible ways are found to implement the carbon reductions, the cases analyzed in the study are judged to yield energy savings that are roughly equal to or greater than costs. Third, a next generation of energy-efficient and low-carbon technologies promises to enable the continuation of an aggressive pace of carbon reductions over the next quarter century.

1.1 OBJECTIVES OF THE REPORT

The purposes of this study are threefold:

1. To provide a quantitative assessment of the reduction in energy consumption and carbon emissions that could result by the year 2010 from a vigorous national commitment to accelerate the development and deployment of cost-effective energy-efficient and low-carbon technologies;

2. To document the costs and performance of the technologies that underpin a year 2010 scenario in which substantial energy savings and carbon emissions reductions are achieved;

3. To illustrate the potential for energy-efficiency and renewable energy R&D to produce further reductions in energy use and carbon emissions by the year 2020.

1.2 METHODOLOGY

To achieve these objectives, we started with the *Annual Energy Outlook 1997* (AEO97) reference case forecasts for the year 2010 (Energy Information Administration, 1996). After thoroughly reviewing these forecasts on a sector-by-sector basis, and working with EIA staff, we chose to accept the EIA "business-as-usual" (BAU) scenario as is for buildings and industry. We modified some of the

assumptions and data to produce a new BAU case – not greatly different from the EIA case – for the transportation and the electric utility sectors.[2]

We then assembled existing information on the performance and costs of technologies to increase energy efficiency or, for selected end-uses, to switch from one fuel to another (e.g., from electricity to natural gas for residential end-uses or from gasoline to biofuels for transportation). For the buildings sector, the technology performance and cost data base are extensive. For transportation, the data base – although less fully developed than for buildings – is sufficient for our purposes. For industry, only partial information on technologies and costs is presently available. As a result, the analysis for industry relies primarily on historical relations between energy use and economic activity and much less on explicit technological opportunities. The industrial analysis also includes some examples of industrial low-carbon technologies. The analysis of low-carbon supply technologies in the electricity sector is based on a review of the literature including detailed technology characterizations prepared by DOE in conjunction with its national laboratories and industry.

Next we created scenarios of increased energy efficiency and lower carbon emissions using the technology data (or, in the industrial sector, historical relations) as key inputs. We chose to run three scenarios other than the BAU case. We have termed the first the "efficiency" (EFF) case. It assumes that the United States increases its emphasis on energy efficiency through enhanced public- and private-sector efforts. The general philosophy of the efficiency case is that it reduces, but does not eliminate, various market barriers and lags to the adoption of cost-effective energy efficiency technology.[3]

The other two cases, dubbed the $25 permit and the $50 permit "high-efficiency/low-carbon" (HE/LC) cases, describe a world in which, as a result of commitments made on a climate treaty or other factors, the nation has embarked on a path to reduce carbon emissions. Both of these cases assume a major effort to reduce carbon emissions through federal policies and programs (including environmental regulatory reform), strengthened state programs, and very active private sector involvement. Both also include a focused national R&D effort to develop and transform markets for low-carbon energy options (e.g., fuel cells for microcogeneration in buildings and advanced turbine systems for combined heat and power in industry). The difference between the two HE/LC cases is in the assumption of a carbon permit price resulting from a domestic trading scheme for carbon emissions with a cap on U.S. emissions (or from equivalent policy measures that increase the price of carbon-based fuels relative to those with less carbon). We assume a domestic permit price of $25 and $50 per tonne of carbon for the two cases. Both of these HE/LC cases include a program of research, development, demonstration and diffusion that is more vigorous than in the efficiency case. In the buildings and industry sectors, the carbon price signal, combined with policies promoting energy efficiency, is believed to trigger most of the additional carbon reductions. In the transportation sector, it is the R&D-driven technology breakthroughs that generate the bulk of the carbon reductions beyond the efficiency case. For the electricity sector, higher prices for carbon-based fuels cause larger shifts from coal to natural gas; for this sector, these same higher relative prices combined with federal and private research, development, and demonstration can bring advanced low-carbon technologies to market.

Although most of the analysis focuses on 2010, we also look beyond this date. Here we describe new technologies, materials, processes, manufacturing methods, and other R&D advances that promise to offer significant energy benefits by the year 2020; for this time period, we make no effort to forecast specific levels of market penetration, energy savings, or carbon reductions. Thus, instead of creating scenarios we describe the technological innovations that could enable the continuation of an aggressive pace of decarbonization well into the next quarter century, if appropriate investments in R&D were made.

1.3 BACKGROUND

The decade of gains in energy productivity achieved by the U.S. following the 1973-74 Arab oil embargo represents a period of economic growth that was decoupled from increases in energy consumption, resulting in substantial economic benefits. Between 1973 and 1986, the nation's consumption of primary energy froze at about 74 quads – while the GNP grew by 35%. Starting in 1986, energy prices began a descent in real terms that has continued to the present. As a result, energy demand grew from 74 quads in 1986 to 91 quads in 1995, and carbon emissions have been increasing at a similar pace.

Despite the growth in energy consumption since 1986, the U.S. economy today remains more energy productive than it was 25 years ago. In 1970, 19.6 thousand Btu of energy were consumed for each (1992) dollar of GDP. By 1995, the energy intensity of the economy had dropped to 13.4 thousand Btu of energy per (1992) dollar of GDP. The U.S. Department of Energy (DOE) estimates that the country is saving $150 to $200 billion annually as a result of these improvements.

Nevertheless, many cost-effective energy-efficient technologies remain underutilized, as discussed in Chapter 2. A host of market barriers account for these lost opportunities. And declining energy R&D expenditures may cause promising technology options to be foregone.

The rationale for government support of energy-efficiency R&D is strong. Much energy-efficiency research is both long-term and high-risk and therefore is not adequately funded by the private sector – despite the possibility of sizable gains in the long run. Furthermore, advances in energy efficiency offer substantial public benefits (such as carbon reductions and improved national security through greater oil independence) that cannot be fully captured in the private marketplace.

The benefits of past public investments in energy-efficiency R&D have been well documented. Between 1978 and 1996, DOE spent approximately $8 billion on energy-efficiency research, development and demonstration (RD&D). Just five of the technologies that were developed or demonstrated with a fraction of this DOE support have resulted in net benefits of $28 billion through 1996. Many other R&D successes have produced technologies yielding substantial energy and cost savings in the market. The DOE RD&D portfolio has also led to significant environmental, health, productivity, and economic competitiveness benefits.

1.4 RESULTS

1.4.1 Prospects for Improved Efficiencies by the Year 2010

Table 1.1 and Figure 1.1 compare the nation's primary energy use in quads for the years 1990 and 1997 (projected) with the results of three scenarios for 2010. (We have included only the high-efficiency/low-carbon case at $50/tonne in the table and figure for simplicity.) The $50/tonne HE/LC case shown below does not reflect the energy impacts of the selected low-carbon technologies described later in this summary (e.g., stationary fuel cells for buildings, advanced turbine systems and biomass gasification in industry) or the supply-side options shown in Table 1.4.

Table 1.1 Primary Energy Use in Quads: 1990-2010

			2010		
	1990	1997	Business-as-Usual Case	Efficiency Case	High-Efficiency/ Low-Carbon Case ($50/tonne C)
Buildings	29.4	33.7	36.0	34.1	32.0
Industry	32.1	32.6	37.4	35.4	33.6
Transportation	22.6	25.5	32.3	29.2	27.8
Total	84.2	91.8	105.7	98.7	93.4

Source: Energy use estimates for 1990 come from EIA (1996a, Table 2.1, p. 39). Energy use estimates for 1997 come from forecasts conducted for EIA (1996b). Numbers may not add to the totals due to rounding.

The major observations are as follows:

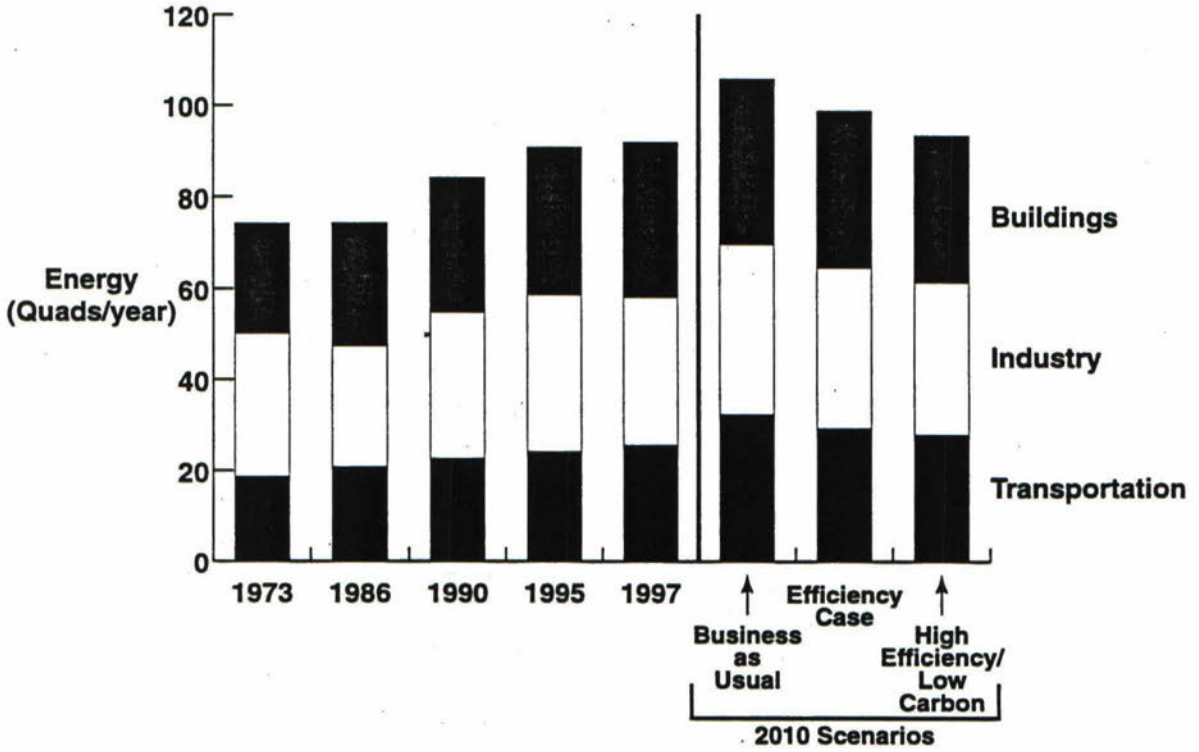
- In the business-as-usual case, energy use increases by 22 quads (26%) between 1990 and 2010; 8 quads of this increase have occurred during the first seven years of this 20-year period. The fastest growing sector during these initial seven years has been buildings (4.3 quads) followed by transportation (2.9 quads) and industry (0.5 quads). In the BAU case, the fastest growing sector during the remaining 13 years is transportation (6.8 quads). This is followed by industry (4.8 quads) and then buildings (2.3 quads). The rapid projected growth in the energy consumed for transportation is driven by estimates of increased per capita travel and minimal fuel efficiency gains.

- The efficiency scenario cuts the overall growth between 1990 and 2010 from 22 to 15 quads. This is a 17% increase over the level of energy consumption in 1990, down from a 26% increase in the BAU case. Relative to the BAU case, the efficiency scenario for transportation delivers slightly more energy savings (3.1 quads) than do the same scenarios for the industrial (2.0) or buildings (1.9) sectors. Compared with 1997 levels, the smallest increase in energy growth for this case is in buildings (0.4 quads), followed by industry (2.8 quads), and transportation (3.7 quads).

- The high-efficiency/low-carbon scenario with a $50/tonne carbon charge further decreases the overall growth between 1990 and 2010, reducing it from 22 to 9 quads. This is an 11% increase over the level of energy consumption in 1990. Relative to the BAU case, the high-efficiency/low-carbon scenario for buildings, industry, and transportation delivers energy savings ranging from 3.8 to 4.5 quads for each sector. Compared with 1997 levels, the buildings sector is down about 2 quads and industry and transportation are up 1 and 2 quads, respectively.

Table 1.2 documents the impact of these projected energy savings in 2010 on carbon emissions in that same year. It also presents the results of the HE/LC scenarios with both $25 and $50 per tonne carbon charges. These scenarios show significant carbon reductions from the combination of greater efficiency improvements and increased use of advanced low-carbon technologies.[4] In these cases, a number of low-carbon technologies have high rates of adoption (e.g., advanced turbine systems and biomass gasification in industry), the utility grid is dispatched to reduce carbon emissions (by using many coal plants for intermediate power and by running more natural gas plants as base load), a set of coal-based power plants are repowered, nuclear plant lifetimes are extended, and key renewable energy technologies are deployed. In all cases, these technologies and measures are estimated to be cost-effective with a differential carbon fee of $50/tonne.

Figure 1.1 Primary Energy Use in Quads: 1990-2010



Note: The high efficiency/low carbon scenario values represent the $50 per tonne carbon charge.

Table 1.2 Carbon Emissions (MtC): 1990-2010

			2010			
			Business-as-Usual (BAU) Case[a]	Efficiency Case	High-Efficiency/ Low-Carbon[b]	
	1990	1997			$25/tonne	$50/tonne
Buildings	460	511	571	546	527	509
Industry	452	482	548	520	494	455
Transportation	432	486	616	543	528	513
Utilities[c]	–	–	–	–	-48	–136
Total (rounded)	1340	1480	1730	1610	1500	1340
Change from 1990		140	390	270	160	0
Change from BAU	–	–	–	-120	-230	-390

a Two of these numbers differ from the AEO97 BAU case. The estimate for buildings (571 MtC) is slightly lower than the AEO97 estimate (576 MtC) due to the use of different ratios for converting "other" fuels (i.e., liquid propane gas, kerosene, and coal) to carbon. The estimate for transportation (616 MtC) is higher than the AEO97 estimate (598 MtC) due to the assumption that auto fuel economy does not increase.

[b]This scenario includes the carbon emission reductions resulting from a carbon permit price of $25 or $50/tonne: (1) dispatch of power plants in which natural gas is favored relative to coal, (2) repowering and partial repowering of coal-based power plants to convert to natural gas, and (3) introduction of selected low-carbon technologies to replace conventional ones, primarily in the industrial and utility sectors.

[c]The entries in the last two columns are negative as they correspond to reductions in carbon emissions resulting from the increased use of natural gas and low-carbon technology for electricity generation as a result of the $50/tonne carbon permit price in this scenario.

Table 1.2 presents results for the business as usual and three efficiency and/or low carbon cases in 2010 as point estimates, because they are meant to be scenarios. When we use these scenarios for analysis, in section 1.5, we describe sources of uncertainty and the effects of uncertainty on our understanding of the implications of these cases. For now, we only describe the different cases.

Figures 1.2 and 1.3 complement the above table by illustrating the carbon emissions reductions from each scenario. The major observations are:

- In the BAU case, carbon emissions are forecast to increase by approximately 390 million tonnes from 1990 levels.

- The energy-efficiency gains incorporated in the efficiency case cut overall growth between 1990 and 2010 by one-third (from 390 to 270 million tonnes). This represents a carbon increase of 20% above 1990 emissions.

- The HE/LC scenario with $25/tonne carbon charge has the potential to reduce carbon emissions by 230 million tonnes from the BAU case in 2010. The largest part of these carbon reductions are from increased efficiency, but major changes in electricity supply (retirements of coal plants, repowering, and carbon-based dispatching) contribute 34 million tonnes, and other low-carbon technology, particularly renewables and advanced turbine systems, produce another 14 million tonnes.

- The HE/LC scenario with $50/tonne carbon charge has the potential to reduce carbon emissions by approximately 390 million tonnes, thereby achieving 1990 carbon emission levels in 2010. Of this 390 million tonne carbon reduction, 205 million tonnes are from increased energy efficiency, 135 million tonnes results from increases in the use of low-carbon fuels and technologies in the utility sector, and 50 million tonnes results from the use of low-carbon technology in industry and transportation.

  Ninety-five million of the 135 million tonnes of carbon reductions in the utility sector comes from retirement of coal power plants and carbon-ordered dispatching of the utility system (including optimization of capacity expansion and unit commitment) and from repowering coal plants with natural gas. These are cost-effective with a $50/tonne carbon charge. The remaining 41 million tonnes are from renewables (wind, co-firing coal-based power plants with biofuels, expansion of hydropower capacity), nuclear power plant life extensions, and power plant efficiency improvements.

  The 50 million tonnes of carbon reductions in industry and transportation from low-carbon technologies are about equally divided among: (1) advanced combustion turbine cogenerators in industry, (2) biomass and black liquor gasification and low-carbon industrial processes, and (3) cellulosic ethanol/gasoline blends for automobiles.

- Approximately 140 MtC of the increase in carbon emissions between 1990 and 2010 will have occurred by the end of 1997; thus, it is useful to look at the 13-year forecast starting with 1997. The carbon reductions incorporated in the efficiency case cut the overall *growth* in carbon emissions between 1997 and 2010 from 250 million tonnes (as forecast in the BAU case) to 130. The HE/LC scenario with $50/tonne carbon charge *reduces* carbon emissions in 2010 by an additional 270 million tonnes.

Figure 1.2 Reductions in Carbon Emissions from Each Scenario

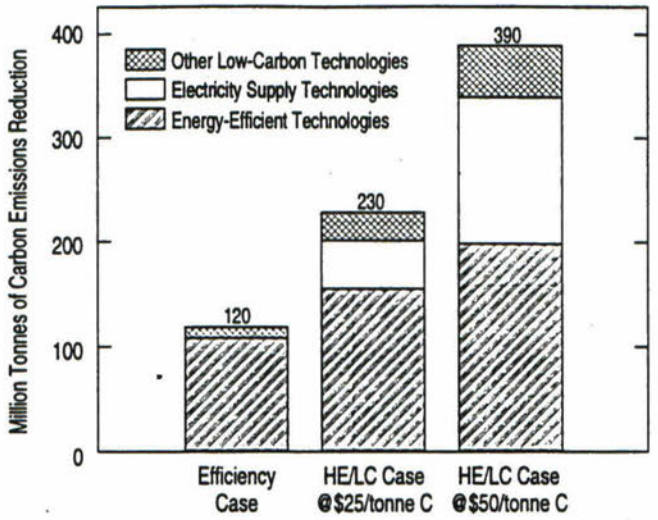


Figure 1.3 Reductions in Carbon Emissions from Each Type of Technology

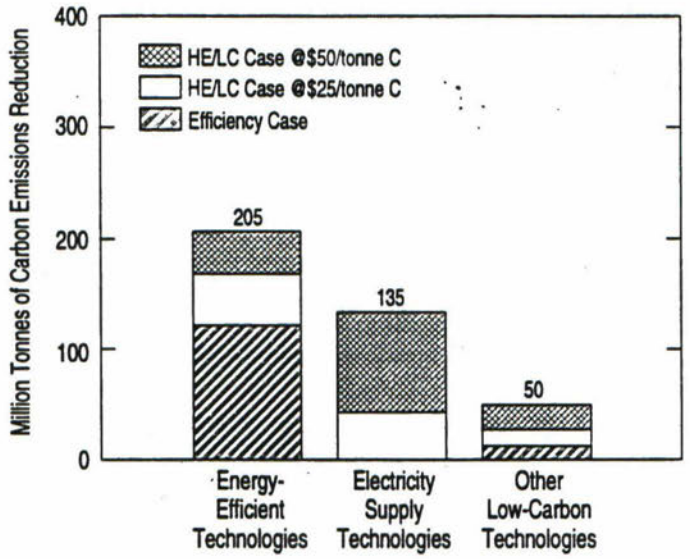


Table 1.3 provides a comparison of the growth rate in energy and in carbon emissions for the four cases, from 1997 to 2010. For the BAU and efficiency cases, the growth in carbon emissions is slightly more rapid than the increase in energy demand. For the HE/LC case with a $50/tonne carbon charge, carbon emissions decline while energy consumption rises. The carbon reduction reflects the increased deployment of low-carbon fuels and technologies as a consequence of the relative increase in price of carbon-based fuels precipitated by the $50/tonne incentive.

It is useful to compare the scenarios in this study to those of other studies. The 1991 report by the Office of Technology Assessment (OTA) titled *Changing by Degrees* (U.S. Congress, 1991) analyzed the potential for energy efficiency to reduce carbon emissions by the year 2015, starting with the base year of 1987. Its "moderate" scenario results in a 15% rise in carbon emissions, from 1300 MtC/year of carbon in 1987 to 1500 MtC/year of carbon in 2015 (compared to a BAU forecast of 1900 MtC/year). Its "tough" scenario results in a 20% to 35% emissions reduction relative to 1987 levels,

or emissions levels of 850 to 1000 MtC/year of carbon in 2015. Our efficiency and HE/LC cases ranging from 1.3 to 1.6 billion tonnes of carbon emissions in 2010 are comparable to OTA's "moderate" case and show considerably higher emissions than OTA's "tough" case.

Table 1.3 Average Annual Energy and Carbon Growth Rates, 1997 to 2010, for Four Cases

	Business-As-Usual (BAU)	Efficiency Case	High Efficiency/ Low Carbon Case ($25/tonne)	High Efficiency/ Low Carbon Case ($50/tonne)
Gross Domestic Product (GDP)[a]	1.88%	1.88%	1.88%	1.88%
Energy Demand	1.09%	0.56%	0.34%	0.13%
Carbon Emissions	1.24%	0.65%	0.11%	-0.75%
Energy Consumption Per GDP (E/GDP)	-0.77%	-1.30%	-1.51%	-1.71%
Carbon Emissions Per GDP (C/GDP)[b]	-0.63%	-1.20%	-1.73%	-2.58%

[a] The Gross Domestic Product (GDP) in 1995 was $7251 billion in 1995 dollars. The 1.88% annual growth was assumed to apply to the entire period, 1995-2010 to derive the results above.

[b] The carbon decrease per unit GDP growth for 1990 to 2010 is 0.7%, 1.1%, 1.4% and 1.9% per year for the reference, efficiency, $25/tonne HE/LC, and $50/tonne HE/LC cases, respectively.

Another benchmark is provided by the 1992 National Academy of Sciences (NAS) report on *Policy Implications of Greenhouse Warming* (National Academy of Sciences, 1992). This study identified a set of energy conservation technologies that had either a positive economic return or that had a cost of less than $2.50 per tonne of carbon. Altogether, NAS concluded that these technologies offer the potential to reduce carbon emissions by 463 million tonnes, with more than half of these reductions arising from cost-effective investments in building energy efficiency. Our efficiency and HE/LC cases suggest the potential for reducing carbon emissions by between 120 and 380 million tonnes by the year 2010. One reason that the NAS estimate is higher is because it is not limited to the 2010 time frame, but rather characterizes the full potential for carbon reductions. Thus, it did not take into account the replacement rates for equipment and processes, and other factors that prevent the instantaneous, full market penetration of cost-effective energy-efficient and low-carbon technologies.

1.4.2 R&D's Potential for Further Benefits by 2020

If carbon reductions in 2010 and beyond are to be sustained at reasonable cost, vigorous R&D efforts are needed to fill the pipeline of next-generation energy technologies. It is difficult to estimate the carbon savings that will accrue from these technologies; however, our effort to characterize their features suggests that an aggressive pace of carbon reductions over the next quarter century can be sustained, with a sufficient investment in R&D. Our analysis of R&D potential for the year 2020 focuses on opportunities for improved energy-efficiency and renewable energy technologies. The potential long-term contributions of carbon sequestration, advanced coal technologies, and nuclear power may also be significant. However, the treatment of vigorous R&D initiatives to improve these supply options after 2010 is beyond the scope of this report.

For an assessment of the broad range of R&D opportunities to reduce U.S. greenhouse gas emissions, based on a 30-year planning horizon, the reader is referred to a report by 11 DOE national laboratory directors (DOE National Laboratory Directors, 1997). That effort examines the potential of science and technology-based developments in energy efficiency, clean energy, and carbon sequestration to produce carbon reductions in each of the next three decades.

Renewable energy technologies will likely play a crucial role in limiting carbon emissions over the long term. Low-carbon energy supply options are needed to fuel domestic and international economic development without stimulating further global warming. Although renewable resources account for only 7% of the nation's total energy consumption at present, many believe that they are at the beginning of a long-term growth trajectory. With continuing technological development and cost reductions, renewables could become preferred energy resources some time within the next several decades. Early evidence of this transition is seen in the continuing adoption of renewable power systems, including especially wind farms and biomass power systems, even in the face of low gas-fired power generation costs and considerable uncertainty in today's electric energy sector.

With a vigorous and sustained program of research, development and deployment, biomass, wind, photovoltaics, geothermal, and solar thermal technologies could deliver significant quantities of electricity in 2020, thereby substantially displacing carbon emissions. For example, the use of forestry and agricultural residues in biomass power systems continues to be an attractive power option where those residues exist. The successful development of higher-efficiency biomass gasification systems would make this technology competitive in a wider range of applications, including for power systems using dedicated feed stock supply systems. At the same time, biological and agricultural research on biomass production will lead both to higher biomass yields and better species for energy conversion purposes in the future.

A second area in which a vigorous and sustained R&D effort could spawn a range of key improvements is in wind power systems. Potential improvements include:

- Advanced blade shapes that increase wind power capture while reducing stress loads,
- Elimination of gearboxes through development of direct-drive generators,
- Variable speed turbines, and
- Better resource prediction that will increase the value of wind power to power systems operators.

A third area of renewables development that is at the beginning of a long-term growth path is the use of renewables in buildings. Solar daylighting, passive solar designs, solar water heating, and geothermal heat pumps already are cost-competitive in many applications, but are not yet widely used. R&D advances could substantially accelerate their market penetration. In addition, building-integrated photovoltaic products will benefit directly from advances in materials research. The ultimate vision is that many buildings will become "net energy generators" through a combination of renewable energy and energy-efficiency technologies.

In the next quarter century, improved energy-efficiency technologies will result from a combination of incremental advances and fundamental breakthroughs. Incremental improvements in all sectors can be achieved by the greater reliance on more precise and reliable sensors and controls or on lower-cost sensors and controls, often integrated into industrial processes, transportation systems, and buildings. Advanced manufacturing technologies, including rapid prototyping and ultraprecision fabrication, also offer broad opportunities for continuous incremental improvements in energy

efficiency and renewable energy. Breakthroughs in bioprocessing, separations, superconductivity, catalysts, and materials can have wide-ranging impacts on energy efficiency and carbon emissions by the year 2020. Examples of specific technology opportunities are described in this report, by sector.

Six R&D areas offer great promise to reduce significantly the energy requirements of our nation's buildings in 2020:

- Advanced construction methods and materials,
- Adaptive building envelopes,
- Multi-functional equipment,
- Integrated, advanced lighting systems,
- Improved controls, communications and measurements, and
- Self-powered buildings.

In addition to the broad application of better process modeling, sensors, and controls in industry, many process/industry-specific opportunities for efficiency gains exist. These are described for each of DOE's targeted industries of the future: pulp and paper, chemicals, petroleum refining, glass, aluminum, iron and steel, and metal casting.

Many of the advanced technologies that have the potential to significantly improve the energy efficiency of transportation need considerable R&D investment before they can become commercially available in the year 2020. For example, to achieve fuel economies in the 60-80 miles per gallon (MPG) range and remain affordable and safe, light-duty vehicles will need:

- Breakthroughs in manufacturing processes for composite materials,
- Large reduction in fuel cell costs and/or cost reductions and performance gains in batteries,
- Utra-low rolling resistance tires,
- High-efficiency accessories, and
- Highly aerodynamic designs.

Opportunities for R&D to lead to improvements in the energy efficiency of other transportation modes are also described in this report.

In all, the continued adoption of energy efficient and renewable energy technologies and a steady flow of technology improvements from collaborative R&D programs with industry could make such environmentally friendly technology an attractive option for domestic and global energy economies in the future. With strong public-private partnerships to support the necessary R&D and market transformation activities, ample cost-effective energy products and practices will be available in 2020.

1.5 ASSESSMENT OF COSTS, ENERGY SAVINGS, AND SOURCES OF CARBON REDUCTIONS

The business-as-usual scenario projects an increase of 390 MtC/year between 1990 and 2010. In our efficiency scenario, in which the nation actively pursues policies and programs to promote market acceptance of energy efficiency while expanding commitments to research and development, energy-efficient technologies reduce this growth in carbon emissions by 120 MtC/year. Under a carbon cap and trading system, in which permits for carbon sell for either $25 or $50/tonne C, very substantial carbon reductions appear possible. Detailed results for these cases, showing the sources of the carbon reductions, are contained in Table 1.4. (Summaries of these results were presented in Figures 1.2 and 1.3.) Results indicate that, for the $50/tonne HE/LC case, there is a potential to roughly return to 1990 levels of carbon emissions in 2010. Almost two-thirds of the increase in carbon emissions is eliminated in the case with a $25/tonne carbon charge (Table 1.4).

The estimates in Table 1.4 include ranges for most of the electricity supply options and the other low-carbon technologies. There are no ranges for the efficiency technologies because the models used to estimate their penetration are nonstochastic. When selecting a single estimate for the $50/tonne case, numbers from the low end of the ranges were generally selected in order to be cautious. Because we did not conduct an integrating analysis in which supply options compete against one another, we felt it important to minimize potential overlap by entering the supply options in conservative quantities. Also note that several renewable resources that could play a greater role by 2010 are omitted from Table 1.4; these resources include include photovoltaics, geothermal, solar thermal, and landfill gas.

One should not ascribe too much significance to specific entries in Table 1.4 There are many different technologies, both on the supply and demand side of the energy system, that will compete to achieve carbon reductions in an environment in which policies and economic signals favor such reductions. Thus, for example, Table 4.1 shows advanced turbine systems in industry cutting carbon emissions by 17 MtC/year in 2010, co-firing coal with biomass reducing emissions by the same amount, and other low-carbon supply technologies (wind, nuclear plant extensions, hydropower expansion, and power plant efficiency) contributing 24 MtC/year. The actual choice of technology depends on how the economics of the different systems evolve over time, how the industry to supply technology develops, the nature and speed of deregulation within the utility industry, and numerous other factors that cannot be known today. As such, we do not intend the results in Table 1.4 to be taken as a prediction of one technology over another to achieve carbon reductions. In this instance, we have posited one of many possible mixes of supply technologies. These same comments apply to the demand-side sectors and technologies.

In Table 1.5 we summarize the expected technology costs in 2010, as well as the cost of implementing a carbon permit system. While these costs are necessarily uncertain, they are our best estimates and, in our view, as likely to be high as to be low. We note, however, that we have focused our analysis on technology costs, and have not assessed the viability of specific policies or programs to achieve market acceptance. As described below, we do account for program and policy costs in an approximate manner.

Appendix A-2 describes the calculations used to derive the direct costs and energy cost savings of the cases. The costs considered include the incremental technology investment by consumers and businesses, fuel price increases, and the estimated cost of federal, state, and local programs required to achieve the carbon emission reductions. These constitute the direct costs of the scenarios. The highest of these by far is the incremental investment costs. However, the generally higher first cost

of these technologies is counterbalanced by substantially lower operating costs. The benefits considered are limited to the savings in operating (energy) costs from the technology investments.

Table 1.4 Potential Annual Reductions in Carbon Emissions in 2010, Compared to the Business-As-Usual Forecast for 2010 (MtC)

		High-Efficiency/Low-Carbon Case	
	Efficiency Case	$25/tonne	$50/tonne*
Buildings			
Energy efficiency	25	42	59
Fuel cells		2	3
	25	44	62
Industry			
Energy efficiency	28	44	62
Advanced turbine systems		5	17 (14-24)
Biomass and black liquor gasification, cement clinker replacement, and aluminum technologies		5	14 (13-16)
	28	54	93
Transportation			
Energy efficiency	61	74	87
Ethanol	12	14	16
	73	88	103
Utility Supply Options			
Coal plant retirements and carbon-ordered dispatching		25	55
Converting coal-based power plants to natural gas		9	40 (25-66)
Co-firing coal with biomass		5	17 (16-24)
Wind		2	7 (6-20)
Extending the life of existing nuclear plants		3	5 (4-7)
Hydropower expansions		2	4 (3-5)
Power plant efficiency		2	8 (7-13)
		48	136
Total	**126**	**234**	**394**

*Numbers in parenthesis are ranges, as documented in the text of the report. See Appendix A-1 for a description of the derivation of the results in this table.

We have presented the direct and most easily quantified of the costs and benefits, but have not attempted a full benefit-cost calculation. We do not account for indirect effects of policies (e.g., the reallocation of investment dollars to efficiency investments). We do not account for the increased cost of some R&D programs that are needed to achieve the scenario results nor do we count the benefit of reduced carbon and other pollutant emissions. Also, we have not analyzed any possible redistribution of wealth that could arise from a carbon trading system or other policy to increase the price of carbon-based fuel.

Considering only these direct costs and energy-saving benefits of the scenarios, we have analyzed the economics of carbon emission reductions from two different perspectives in order to establish a credible range of costs. In the first, which we label "optimistic," we evaluate direct costs and energy-saving benefits with a real discount rate that approximates the cost of capital *for efficiency investments* for the different end-use sectors: 7% for buildings, 10% for transportation, and 12.5% for industry.

The lowest discount rate, for buildings, is based on the fact that the money for residential buildings is derived from home mortgages or home improvement loans. The higher rate for industry reflects the fact that energy-efficiency investments have to compete with investments for other projects. These discount rates are not those that describe current market behavior, but rather are reflective of costs of capital if the market did invest in the energy-efficiency measures. For the "optimistic" case, we assume costs for efficiency measures brought about by utility, federal programs, and state programs (e.g., demand-side management programs by utilities, federal market transformation programs) to be 15% of technology costs. We also assume that at least half of the efficiency occurs as a result of federal policies (e.g., standards or carbon permit charges) which add very low direct program costs. Thus, the overall costs of implementation are taken to be about 7% in the "optimistic" case. The electric supply-side technologies are assumed to add an incremental cost of $30/tonne carbon in 2010, based on an average estimate of the incremental costs of the technologies from the appropriate sections of this report.

These programs and policies are not specified in this study, but the broad nature of the actions could include technology R&D partnerships such as the current Partnership for a Next Generation of Vehicles and Industries of the Future; energy efficiency codes and standards; expanded partnerships, technical assistance, and information programs to accelerate the adoption of energy-efficient technologies; incentives through the tax system directed at investments in energy-efficient technology in industry; and a variety of non-federal programs to accelerate market diffusion of energy-efficient and low-carbon technologies.

The second perspective, which we label "pessimistic," assumes that there are hidden costs associated with achieving widespread market acceptance of many of the efficiency and low-carbon technologies, even after the imposition of a carbon charge and the implementation of major policies and programs to promote a low-carbon future. In this perspective, we evaluate costs and benefits at a real discount rate of 15% for buildings and 20% for transportation and industry. Program costs are increased to 30% of the cost of efficiency measures, an estimate that is a high bound compared with federal, state, and utility experience. Overall implementation costs (programs and directed policies) are taken to be 15% of technology investments in this case. Other data and assumptions in this case are the same as for the "optimistic" case.

The results of the economic analysis are presented in Table 1.5. Estimated direct costs are $26-$49 billion per year for the efficiency scenario and $51 to $88 billion per year for the high-efficiency/low-carbon scenario. Estimated energy savings per year in 2010 are $42 to $51 billion per year in the efficiency case and $70-$88 billion per year for the high-efficiency/low-carbon case. The costs, which are a small portion of annual gross private domestic investment of about $1.4 trillion in 2020, are likely to be more than balanced by savings in energy bills. Thus, net costs to the U.S. economy are estimated to be near or below zero in this time frame.

The range of estimates in Table 1.5 reflects our attempt to "bound" optimistic and pessimistic assessments. There are clearly other ways in which these bounds could be described, just as there are many scenarios that could have been analyzed. We reflect a lower or pessimistic bound in three ways. First, we assume the investments in energy efficiency yield only 80% of the estimated energy savings. Second, we value costs and benefits at discount rates noticeably higher than the likely cost

of capital. Third, we increase the estimated cost of programs and policies to twice that of typical experience today. It is worth noting that if the implementation costs were taken to be much higher than we believe to be reasonable – 50% of investments costs for programs and 25% overall – this would add about $10 billion per year to the costs of the high-efficiency/low-carbon in the pessimistic case.

Table 1.5 Estimated Costs and Energy Savings of the Efficiency and High-Efficiency/Low-Carbon Scenarios : Optimistic and Pessimistic View Estimates (billions of 1995$, annualized)

	Efficiency Case[a]			High-Efficiency/Low-Carbon Case[b]		
	Direct Costs[d] (billion 1995$)	Energy Savings[c] (billion 1995$)	Carbon[c] Savings MtC	Direct Costs (billion 1995$)	Energy Savings (billion 1995$)	Carbon Savings MtC
Energy Efficiency						
Buildings	7-14	14-17	20-25	14-26	26-33	49-62
Industry	3-5	6-7	22-27	8-13	12-15	74-93
Transportation	16-30	22-27	58-73	23-43	32-40	82-103
Electricity Dispatch	0	0	0	2	0	44-55
Electricity Repowering	0	0	0	2	0	32-40
Other Low-Carbon Techologies	0	0	0	2	0	33-41
Total	**26-49**	**42-51**	**100-125**	**51-88**	**70-88**	**314-394**

[a] Energy efficiency category includes ethanol in transportation.

[b] Energy savings and carbon savings in the HE/LC case are relative to BAU case.

[c] In the "pessimistic" case, we have assumed that only 80% of the carbon savings are achieved, even though the technology and implementation costs are unchanged. The range on carbon savings represents this assumption.

[d] Direct costs include the incremental technology investment cost and the cost of programs and policies required to achieve the carbon emission reductions. Costs are calculated from differing viewpoints: the "optimistic" case uses discount rates that vary between 7% and 12.5% for the different sectors, as described in the text. For the "pessimistic" case, the discount rates used to annualize costs vary between 15% and 20%. Also in this case, the cost of implementing programs (30%) and an overall package of programs and policies (15%) is taken to be twice that of the "optimistic" case.

In addition to these costs, one needs to calculate the impact of the cases on natural gas demand. In all of these cases, natural gas replaces very large quantities of coal. Higher natural gas demand would result in higher natural gas prices, which in turn would increase the cost of substituting natural gas for coal in power production, etc. As it turns out, our scenarios have somewhat reduced gas demand compared with the BAU case (or with AEO97 baseline for 2010, on which the price of natural gas in our work is based). Specifically, demand for natural gas in the HE/LC ($50/tonne) case declines in 2010 by 2 quads compared with the business-as-usual case. This is the result of declines of 0.5 quads for buildings, 1.0 quads for industry, and 0.5 quads for electricity. The latter occurs because of the balance among three factors: increase in gas demand because of the large-scale substitution of natural gas for coal, decrease of gas demand because of the use of many low-carbon technologies that do not use natural gas (wind, nuclear power plant extensions, power plant efficiency upgrades, hydropower expansion, co-firing with biofuels), and the large increase in cogeneration, which reduces demand for natural gas for heating applications.

The sum of the second and third effects are somewhat greater than the first, and thus total natural gas demand associated with electricity generation declines. This could reduce the cost of natural gas, a benefit that we have not included in the analysis.

The $50/tonne carbon charge, while not constituting a direct cost, does represent a potentially large transfer payment. The magnitude of the transfer payment, as well as the losers and winners from the transfers, depends on the nature of policy and its implementation as a cap and trade system or some alternative. The amount of money that could be in play is very large: $50/tonne times 1.3 billion tonnes per year equals $65 billion per year.

In short, while there will surely be winners and losers for these energy-efficiency and low-carbon scenarios, our analysis shows that their net economic costs – under a range of assumptions and alternative methods of cost analysis – will be near or below zero.

The achievability of the cases depends on many factors. In all cases, carbon reductions require the nation to embark on an aggressive set of policies and programs. Such efforts could occur in response to an international agreement on climate change or to other events that result in a national determination to reduce the growth of carbon emissions. In the high-efficiency/low-carbon cases, we assume a vigorous national program of research, development, demonstration, and diffusion, and a trading regime for carbon with a domestic permit price of either $25/tonne or $50/tonne carbon. Without some scheme that provides strong incentives for switching from coal to natural gas, and for deploying other low-carbon technologies, much of the potential for carbon reductions will not be realized.

Government policies and programs that encourage and/or require the adoption of energy-efficiency and low-carbon technologies will be needed, along with incentives for industry to invest more in these technologies. Additional private and public investments are necessary, not only to accelerate the introduction of new technologies into the market before 2010 but also to ensure the availability of technologies for the period after 2010. The transportation and utility sectors are especially dependent on early technological advances to achieve the scenario results in 2010.

There is no assurance that these and other driving forces will cause the scenarios we have described to take place. Our major conclusion is that technology can be deployed to achieve major reductions in carbon emissions by 2010 at low or no net direct costs to the economy. Cost-effective energy efficiency alone can take the nation 30 to 50% of the way to 1990 levels. Two additional utility sector measures can reduce carbon emissions by another 30% at an estimated cost of $50/tonne carbon: carbon-based dispatch and conversion of existing power plants from coal to natural gas.[5] Finally, we identify several additional technologies that can contribute up to 20% of the estimated carbon reductions, also for less than $50/tonne. A next generation of advanced energy-efficiency and renewable energy technologies promises to enable the continuation of an aggressive pace of energy and carbon reductions over the next quarter century.

1.6 REFERENCES

DOE National Laboratory Directors. 1997. *Technology Opportunities to Reduce U.S. Greenhouse Gas Emissions*, draft, September.

Energy Information Administration (EIA). 1996. *Annual Energy Outlook 1997: With Projections to 2105*, DOE/EIA-0383(97) (Washington, DC: U.S. Department of Energy), December.

National Academy of Sciences (NAS). 1992. *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base* (Washington, DC: National Academy Press).

Office of Technology Assessment (OTA). 1991. *Changing by Degrees: Steps to Reduce Greenhouse Gases*, OTA-0-482 (Washington, DC: U.S. Government Printing Office) February.

ENDNOTES

[1] The five national laboratories participating in the study were: Argonne National Laboratory (ANL), Lawrence Berkeley National Laboratory (LBNL), National Renewable Energy Laboratory (NREL), Oak Ridge National Laboratory (ORNL), and Pacific Northwest National Laboratory (PNNL). LBNL and ORNL were the co-leaders of the effort.

[2] The differences between the AEO97 BAU case and ours for 2010 are (1) 1.2 quads higher use of oil in transportation (32.3 instead of 31.1 quads) because auto fuel economy does not increase and (2) lower use of oil for electricity generation (declines from 1.5% of generation to 0.1%) and slightly higher use of natural gas and coal. In all other regards, including price of all fuels and delivered energy, our reference case and the AEO BAU case are essentially identical.

[3] See Section 2.2.3 for a definition of cost-effective energy efficiency technology.

[4] $50 per tonne of carbon corresponds to 12.5 cents per gallon of gasoline or 0.5 cents per kilowatt-hour for electricity produced from natural gas at 53% efficiency (or 1.3 cents per kilowatt-hour for coal at 34% efficiency). $25 per tonne would cut these gasoline and electricity price increments in half.

[5] The cost curve for repowering is relatively flat; as such, considerable additional reductions are possible at a cost not too different from $50/tonne. The results are highly sensitive to the price differential between coal and natural gas; at a lower (higher) price differential, a higher (lower) permit price of carbon is needed.

Chapter 2
INTRODUCTION AND BACKGROUND

This report presents the results of a multi-laboratory study aimed at quantifying the potential for energy-efficient and low-carbon technologies to reduce carbon emissions in the United States. The stimulus for this study derives from a growing recognition of the link between energy R&D and the nation's ability to respond to international calls to reduce the growth of greenhouse gas emissions. According to a recent report of the Intergovernmental Panel on Climate Change (IPCC), the earth's surface temperature has increased about 0.2 degrees Celsius per decade since 1975. Further, the IPCC report concluded that "the balance of evidence suggests that there is a discernible human influence on global climate" as the result of activities that contribute to the production of greenhouse gases (IPCC, 1996, p. 5). By preventing heat radiated from the sun-warmed earth from escaping into space, the increased concentration of greenhouse gases in the atmosphere contributes to global warming.

The major greenhouse gases are carbon dioxide (CO_2), methane (CH_4), ozone (O_3), nitrous oxide (N_2O), water vapor (H_2O), and a host of engineered chemicals such as chlorofluorocarbons (CFCs). CO_2 accounts for a majority of recent increases in the heat-trapping capacity of the atmosphere, with worldwide atmospheric concentrations of CO_2 increasing at about 0.5% annually. Anthropogenic CO_2 has resulted in atmospheric CO_2 concentrations that exceed pre-industrial levels by 30%. Of all the human activities that contribute to these increases, fossil fuel combustion is by far the largest, accounting for almost 60% of the greenhouse warming resulting from anthropogenic sources in recent years (NAS, 1992, Table 2.2, p. 8). Energy-efficient, renewable energy, and other low-carbon technologies reduce CO_2 emissions by displacing the need for fossil fuel combustion; hence, this report focuses primarily on this single greenhouse gas. Throughout the report, the potential climate benefits of energy-efficient and low-carbon technologies are quantified in terms of reductions in millions of metric tons of carbon (MtC) emitted.[1]

Analysis by a number of key climate and energy modelers indicates that significant research and development on greenhouse-friendly technologies is essential to achieving meaningful emission-reduction targets at affordable costs. As a result, climate change is becoming a major impetus for energy R&D programs and is likely to grow in importance in the future. By documenting the emissions reductions that past energy-efficiency and renewable energy R&D can deliver by the year 2010, and by describing the potential for future research to reduce carbon emissions even farther, this report is intended to inform a broad public about technology-based approaches to reduce greenhouse gas emissions.

2.1 OBJECTIVES OF THE STUDY

The purposes of this study are threefold:

1. To provide a quantitative assessment of the reduction in energy consumption and carbon emissions that could result by the year 2010 from a vigorous national commitment to accelerate the development and deployment of cost-effective energy-efficient and low-carbon technologies;

2. To document the costs and performance of the technologies that underpin a year 2010 scenario in which substantial energy savings and carbon emissions reductions are achieved;

3. To illustrate the potential for energy-efficiency and renewable energy R&D to lead to further reductions in energy use and carbon emissions by the year 2020.

The report focuses on energy-efficiency and renewable energy R&D. The coverage of additional selected low-carbon end-use and electricity supply options was based in large measure on their perceived potential to contribute significantly to reducing carbon emissions by 2010.

2.2 METHODOLOGY

2.2.1 Overview

To achieve these objectives, we started with the *Annual Energy Outlook 1997* (AEO97) reference case forecasts for the year 2010 (Energy Information Administration, 1996). After thoroughly reviewing these forecasts on a sector-by-sector basis, and working with EIA staff, we chose to accept the EIA "business-as-usual" (BAU) scenario as is for buildings and industry and to modify some of the assumptions and data and produce a new BAU case – not greatly different from the EIA case – for the transportation and the electric utility sectors.

We then assembled existing information on the performance and costs of technologies to increase energy efficiency or, for selected end-uses, to switch from one fuel to another (e.g., from electricity to natural gas for residential end-uses or from gasoline to biofuels for transportation). For the buildings sector, the technology performance and cost data base are extensive. For transportation, the data base – although less fully developed than for buildings – is sufficient for our purposes. For industry, only partial information on technologies and costs is presently available. As a result, the analysis for industry relies primarily on historical relations between energy use and economic activity and much less on explicit technological opportunities. The industrial analysis also includes some examples of industrial low-carbon technologies. The analysis of low-carbon supply technologies in the electricity sector is based on a review of the literature including detailed technology characterizations prepared by DOE in conjunction with its national laboratories and industry.

Next we created scenarios of increased energy efficiency and lower-carbon emissions using the technology data (or, in the industrial sector, historical relations) as a key input. We chose to run three scenarios other than the BAU case. We have termed the first the "efficiency" case. It assumes that the United States increases its emphasis on energy efficiency through enhanced public- and private-sector efforts. The general philosophy of the efficiency case is that it reduces, but does not eliminate, various market barriers and lags to the adoption of cost-effective energy-efficient technology.

The other two cases, dubbed the $25 permit and the $50 permit "high-efficiency/low-carbon" (HE/LC) cases, describe a world in which, as a result of commitments made on a climate treaty or other factors, the nation has embarked on a path to reduce carbon emissions. Both of these cases assume a major effort to reduce carbon emissions through federal policies and programs (including environmental regulatory reform), strengthened state programs, and very active private sector involvement. Both also include a focused national R&D effort to develop and transform markets for low-carbon energy options (e.g., fuel cells for microcogeneration in buildings and advanced turbine systems for combined heat and power in industry). The difference between the two HE/LC cases is in the assumption of a carbon permit price resulting from a domestic trading scheme for carbon emissions with a cap on U.S. emissions (or from equivalent policy measures that increase the price of carbon-based fuels relative to those with less carbon). We assume a domestic permit price of $25 and $50 per tonne of carbon for the two cases. Both of these HE/LC cases include a program of research, development, demonstration and diffusion that is more vigorous than in the efficiency case. In the

buildings and industry sectors, the carbon price signal, combined with policies promoting energy efficiency, is believed to trigger most of the additional carbon reductions. In the transportation sector, it is the R&D-driven technology breakthroughs that generate the bulk of the carbon reductions beyond the efficiency case. For the electricity sector, higher prices for carbon-based fuels cause larger shifts from coal to natural gas; for this sector, these same higher relative prices combined with federal and private research, development, and demonstration can bring advanced low-carbon technologies to market.

Although the work focuses on 2010, we also look beyond this date. Here we describe new technologies, materials, processes, manufacturing methods, and other R&D advances that promise to offer significant energy benefits by the year 2020; for this time period, we make no effort to forecast specific levels of market penetration, energy savings, or carbon reductions. Thus, instead of creating scenarios we describe the technological innovations that could enable the continuation of an aggressive pace of decarbonization well into the next quarter century, if appropriate investments in R&D were made.

2.2.2 Time Frame

Analysis for all sectors focuses on two base years (1990 and 1997) against which future progress is benchmarked, and a target year of 2010 for assessing emissions reduction potential. Energy use and emissions for 1990 and 1997 are used to compare future energy consumption and carbon emissions. The report examines a "snapshot" of energy use and carbon emissions, by sector, in 2010. The increased use of energy-efficient technologies combined with the development of new technologies based on past R&D plus an invigorated R&D effort initiated in 2000 are needed to achieve our 2010 scenarios. Intermediate years between 1997 and 2010 are not examined.

We also highlight the likely post-2010 benefits of an intensified investment in energy R&D. This captures the effects of technologies that may not be widely commercial for some years but that could deliver cost-effective energy savings and emissions reductions, if public and privately supported R&D were to accelerate their proof of concept and reduce their developmental risks.

2.2.3 End-Use Efficiency Scenarios

Each of the three end-use sector chapters is consistent in terms of overall approach, scope, and time frame. They each analyze three scenarios for the year 2010: a business-as-usual case, an efficiency case, and a high-efficiency/low-carbon case. (In the integration of this work, we later assess two different HE/LC cases – one with a $25/tonne carbon charge and the other with a $50/tonne carbon charge.) The buildings sector also presents a "frozen efficiency" baseline, for additional comparison purposes. While there is variation in the methodologies used to estimate the energy savings and emission-reduction potential of each sector, the three sector chapters are similar in using a combination of technology analysis and model-based forecasting. Specifically, the buildings and transportation sectors use stock models with technology characteristics and other parameters taken from assessments of individual technologies. The industrial sector forecasts conservation investment behavior based on econometric modeling with industry-specific conservation supply curves as inputs.

All of the scenarios described in this report use the AEO97 forecasts of national economic output as measured by gross domestic product (GDP), which is projected to increase by 1.9% per year through 2015. Similarly, the buildings sector uses the AEO97 forecast of annual growth in residential (1.1%) and commercial (0.9%) floorspace; the industrial sector uses the AEO97 assumption of a 2.1% annual growth rate for manufacturing production; and the transportation sector uses the AEO97 forecast of a 1.5% annual increase in vehicle miles traveled and a 3.7% annual increase in air travel.

The scenarios for each sector also use the AEO97 energy price forecasts. World oil prices are assumed to rise from $17 per barrel in 1995 to $20.4 per barrel (in 1995$) in 2010. In AEO97, natural gas prices increase at annual rates of 1.4%, with larger increases in prices to the industrial, electricity, and transportation sectors offsetting reductions in prices to residential and commercial consumers. Between 1995 and 2010, the average price of electricity is projected to decline by 0.6% a year as a result of competition among electricity suppliers. Electricity prices are forecast to decrease the most for industrial customers and the least for residential customers.

Such macroeconomic and fuel price assumptions strongly influence the rate of penetration of energy-efficient technologies in each sector. Further details regarding these assumptions can be found in EIA (1996c).

Frozen Efficiency Baseline. This case, which is analyzed only for the buildings sector, assumes that energy-consuming equipment and systems existing in the year 1997 remain at the same efficiency until they are retired. This equipment and these systems retire over the 1997-2010 period at a rate based on standard equipment lifetimes. It assumes that all new equipment employed after 1997 remains at the efficiency of new devices in the year 1997. The frozen efficiency baseline provides an upper bound to likely energy demand (under the economic assumptions applied to all the cases), because it ignores all forces leading to higher efficiency of new equipment in the business-as-usual case. It also ignores any retrofits that might take place if there were economic reasons for early retirement of equipment.

This case is presented primarily for heuristic reasons: it describes an easily-understood case in which technology does not change. This is useful for exploring the impacts of technology change. Also, the case is not necessarily divorced from reality: in the era of low energy prices preceding the oil embargo of 1973-74, the energy efficiency of many household, transportation, and industrial technologies changed very little.

Business-as-Usual Case. The business-as-usual (BAU) case represents the best estimate of future energy use given current trends in service demand, stock turnover, and natural progress in the efficiency of new equipment. It assumes that R&D and implementation programs at DOE and EPA continue at more or less current levels, without a significant influx of new funding. It captures likely changes in efficiencies of new equipment over the analysis period. It also allows for some early retirement of equipment where cost savings from new energy-efficient products are high relative to purchase and installation costs, as in some industrial motor and drive systems and commercial lighting retrofits.

To create this scenario, the buildings and industry sectors adopted the AEO97 reference case as their BAU cases. For the transportation sector, we modified AEO97 somewhat. Specifically, the AEO97 reference case forecasts that the efficiency of passenger cars will increase from 27.5 MPG in 1997 to 31.5 MPG in 2010. We believe such improvements are unlikely in the absence of increases in real gasoline prices and hence our BAU case for transportation leaves the MPG performance of light-duty vehicles in 2010 unchanged from 1997 performance.

Efficiency Case. The efficiency case describes the potential for cost-effective, energy-efficient technologies to penetrate the market by the year 2010, given an invigorated public- and private-sector effort to promote energy efficiency through enhanced R&D and market transformation activities. This case assumes that national policy, possibly in combination with exogenous events, leads to an increase in the cost-effectiveness and deployment of energy-efficient technologies. Cost-effectiveness is improved because R&D, in combination with increased deployment efforts, result in declining capital costs. We do not specify the policies or exogenous events that could precipitate

such changes. Instead, we examine the potential for technology-based energy and carbon reductions, assuming that significant efforts are undertaken to enhance the attractiveness of these technologies.

To be attractive to manufacturers and consumers, a technology must be cost-effective. Thus, this scenario limits itself to describing the potential for cost-effective technologies to reduce energy use and carbon emissions. A technology is defined as "cost-effective" if it delivers a good or service at equal or lower life-cycle costs relative to current practice.[2] Externalities are not internalized in this definition of cost-effective. An energy-efficient technology may be societally cost-effective, for instance by taking into account its air quality or safety benefits, but not be judged cost-effective by our narrower economic criteria. This scenario reflects the view that "policy options exist that would slow climate change without harming American living standards, and these measures may in fact improve U.S. productivity in the longer run" (Arrow et al., 1997).

Compared to the business-as-usual case, the efficiency case assumes (1) better technology and (2) higher penetration rates for energy-efficient and low-carbon technologies.

1. "Better technology" results from an invigorated public- and private-sector investment in R&D such that energy-efficient technologies become more cost-competitive based on current fuel prices. Performance improvements between 1997 and 2010 are mostly incremental in this scenario, but by 2020 they could be revolutionary.

2. "Higher penetration rates" result from an invigorated set of policies and market transformation programs that reduce market failures and allow markets to operate more efficiently. Through improved information and risk reduction, capital markets for energy-efficiency investments could be strengthened and consumer investment hurdle rates for the purchase of high-efficiency equipment could be lowered.

Despite its assumption of an aggressive public commitment to energy efficiency, this scenario also takes into account real-world experience and program implementation constraints which suggest that it is not reasonable to assume that every consumer will purchase the least-cost, high-efficiency technology option. There are many reasons to expect a shortfall from such a maximum case: capital rationing, imperfect information, misplaced incentives, and the unevenness of supply, installation, and maintenance networks (DOE, 1996b).

High-Efficiency/Low-Carbon Case. The high-efficiency/low-carbon (HE/LC) case assumes a greater commitment to reducing carbon emissions through federal policies and programs, strengthened state programs, and very active private sector involvement. One way to view this case is to see it as an attempt to model a world where an international global warming treaty is negotiated over the next few years and where the outcome for the United States (and other Annex I nations) is to stabilize carbon and other greenhouse gas emissions in 2010 at 1990 levels. The United States pursues those reductions by (1) aggressively instituting federal policies to develop and deploy energy-efficiency and low-carbon technologies, such as increased funding for market transformation and R&D efforts and (2) by issuing tradable emission permits.

In this rendition of the HE/LC case, policies are put into place by 2000 and progressively phased in until they are fully in place by 2010. The permit price for carbon would presumably rise steadily through 2010. Thus, we have multiple factors affecting consumer and business behavior, including the following:

- The recognition that policies to reduce carbon emissions will necessarily follow the signing of an international agreement, including an anticipation of higher relative prices for carbon-based fuels;

- The actual increases over time in the permit price of carbon (which we model as averaging either $25 or $50 per tonne for much of this period);
- Increased federal effort to accelerate R&D and diffusion of low-carbon technologies;
- The development and introduction by other countries of advanced low-carbon technologies; and
- The change in consumer preferences and behavior that would result from an international treaty and national commitment to stabilize greenhouse gases, much like changes in consumer behavior in the aftermath of the oil embargo of 1973-74.

In summary, this scenario for 2010 describes a combination of better technology, "readier" markets, and a price of carbon that results in a significantly increased willingness to manufacture, purchase, and use low-carbon technologies. It represents a vigorous national commitment that goes far beyond current efforts.

2.2.4 Methodological Differences Across Sectors

The operational definitions used to model these scenarios for the individual end-use sectors reflect the above conceptual definitions, but are nevertheless distinct (Table 2.1). These differences are due partly to the modeling approaches used for each sector. They also reflect the authors' sense of what could "drive" significant increases in energy efficiency in each sector. For instance, to achieve a high-efficiency/low-carbon scenario, the transportation analysis postulates a set of technology breakthroughs. The industrial analysis, on the other hand, achieves its high-efficiency/low-carbon scenario by doubling market penetration rates and assuming that energy-efficiency decisions are treated as strategic investments with correspondingly lower hurdle rates.

The sectors also differ in the way that life-cycle costs and benefits are calculated to determine the cost-effectiveness of technologies in their efficiency scenarios.

- The buildings sector employs a 7% real discount rate to value the stream of benefits accruing from an investment. These benefits accumulate throughout the specific operational lifetimes assumed for individual technologies. The efficiency case assumes market penetration of about one-third of the technologies that are cost-effective at a 7% real discount but not adopted in the business-as-usual case. The HE/LC case doubles this penetration.
- The industrial sector assumes a capital recovery factor (CRF) of 15%, rather than 33% (which is the BAU assumption). Thus, to be considered cost-effective in this sector, an investment must pay back in no more than approximately seven years.
- The transportation sector uses a 7% discount rate, but it is applied only to the first five years of operation, even though the expected lifetime of a vehicle may be much longer. This five-year period is meant to reflect the realities of purchase behavior in this sector, and results in decisions that are based on considerably less than the full life-cycle of benefits.

Table 2.1 Conceptual and Operational Definitions of Scenarios for 2010

Scenario/ Definition	Business-as-Usual (BAU)	Efficiency (EFF)	High-Efficiency/ Low-Carbon (HE/LC)
Conceptual Definition	Best estimate of future energy use given current trends in service demand, stock turnover, and natural progress in the efficiency of new equipment, including advances supported by current public-sector programs; assumes no changes in federal energy or environmental policies.	Potential for cost-effective, energy-efficient technologies to penetrate the market given an invigorated effort to promote energy efficiency through enhanced public and private-sector R&D and market transformation activities.	Optimistic but feasible potential for energy efficiency and low-carbon technology based on a greater commitment to reduce carbon emissions resulting from actions that might include the creation of a market value for carbon of $25 and $50 per tonne.
Operational Definitions:			
Buildings	AEO97 reference case developed using the NEMS model.[a]	35% of the difference in total energy savings between the BAU and cost-effective energy savings potential.[b]	65% of the difference in total energy savings between the BAU and cost-effective energy savings potential.
Industry	AEO97 reference case; LIEF is calibrated to this case and then is modified to produce the two efficiency scenarios.	The capital recovery factor (CRF) for energy-efficiency investment used in LIEF is lowered from 33% to 15%.[c]	The CRF is lowered to 15% and the penetration rates for energy-efficient technology used in the BAU are doubled.
Transportation	AEO97 reference case modified to hold new light-duty vehicle fuel economy constant at current levels.	Assumes earlier introduction of advanced fuel economy technology and adds certain key technologies that are not in the BAU.	Postulates breakthroughs in hybrid vehicle technology, major aerodynamic and engine efficiency gains for commercial aircraft, and other technological achievements.

[a] NEMS = National Energy Modeling System developed by DOE's Energy Information Administration.

[b] The cost-effective energy savings potential is defined as the difference between the energy demand that results from using the most energy-efficient of the cost-effective technology currently available or forecasted to be available by 2010, and the energy demand in 2010 assuming business-as-usual rates of technology change and use in the economy.

[c] LIEF = Long-Term Industrial Energy Forecasting model developed by Argonne National Laboratory and Lawrence Berkeley National Laboratory.

2.2.5 What the Study Does Not Do

This report does not describe the policies that might be implemented to achieve higher penetrations of energy-efficient and low-carbon technologies. (Reviews of a wide range of possible policy options can be found in several recent publications, including OTA (1991), NAS (1992), and DOE (1996b)). Rather, this report highlights the potential performance and impacts of technological developments and transformed markets. The existence of cost-effective technologies is a prerequisite for public policies to work. Without the technologies, policies to reduce greenhouse gas emissions will be very costly. Indeed, this analysis suggests that carbon stabilization could produce net benefits if the nation invests significantly in cost-effective energy-efficiency and low-carbon technologies.

Thus, we believe it is critical to understand the availability of technologies, their performance, and their costs for as many end-uses of energy as possible. Armed with this knowledge, discussion of policies becomes much more meaningful. Without it, such discussion is less likely to lead to good decisions. Thus, we choose to focus this report on the more narrow topic of technologies in the belief that doing a credible job in this area will ultimately further the policy dialogue.

A second reason for focusing on technologies is our belief that insufficient attention has been given to the role of R&D on energy-efficient and low-carbon technologies as a means to deal with climate change and other environmental impacts. If effective energy technologies are not developed, then the cost of reducing greenhouse gas emissions (and other environmental impacts of energy) will be very high.

As in the AEO97 reference case, each of the scenarios is completed at the national level. Thus, regional variations in population and economic activity are not considered, nor are regional differences in fuel price, weather, or air quality and environmental conditions that might create regional niche markets for particular technologies. As a result, our analyses have undoubtedly overlooked the possible development of regional markets for advanced energy technologies. A valuable next step would be to conduct analyses at a finer geographic scale to produce national estimates that reflect such regional variations.

2.3 OVERVIEW OF THE REPORT

The rest of Chapter 2 sets the stage for the remainder of this report. It describes historical energy and carbon trends, both at the national level and by sector, as a backdrop for assessing energy consumption and carbon emission forecasts. It also discusses the government's role in energy R&D, including the rationale for government support and some evidence of past energy-efficiency technology successes that benefited from government sponsorship.

Chapters 3 through 5 address each of the major energy end-use sectors: buildings (Chapter 3), industry (Chapter 4), and transportation (Chapter 5). Four tasks are completed for each sector:

1. Energy scenarios with and without a strong efficiency push, focusing on the year 2010, and including comparisons with the AEO97 projections from the National Energy Modeling System;

2. Documentation of the cost and performance assumptions for individual energy-efficient and low-carbon technologies;

3. Development of three scenarios (business-as-usual, efficiency, and high-efficiency/low-carbon cases) for the year 2010 and an explanation of how the scenarios were developed; and

4. Descriptions of new technologies that could become available in the 2010 to 2020 time period, as the result of R&D over the next two decades.

Each of these chapters is accompanied by appendices that provide detailed documentation of the technology assumptions and the forecasting methodologies used. These are labeled Appendices C (buildings), D (industry), and E (transportation).

Chapter 6 analyzes the electricity sector to forecast the effect of electricity and demand savings in the year 2010 on CO_2 emissions from power plants. It also assesses the impact of a $50/tonne permit price for carbon on the generation mix used by the electricity sector in 2010. The results of these analyses are used in the buildings and industry sector chapters to convert electricity savings into carbon reductions. Results from this chapter reveal the importance of fuel choice for new power plants and fuel switching for existing power plants as determinants of carbon emissions in 2010. Specifically, the cost and magnitude of fuel switching from coal to natural gas for power generation, the possible early retirement of some coal-fired plants, and the upgrading/repowering of existing plants were identified as key issues for Chapter 7.

The possible conversion of coal plants to natural gas combined cycle technologies is analyzed in Chapter 7, as one of many electricity supply-side options for reducing carbon emissions by 2010. Other options are addressed in Chapter 7, albeit more briefly, including renewable electricity technologies, efficiency improvements in generation and T&D, advanced coal technologies, and nuclear plant life extension. The chapter also characterizes the carbon reduction benefits that could accrue by the year 2020 from a sustained renewable energy R&D effort.

2.4 HISTORICAL ENERGY TRENDS

2.4.1 National Trends

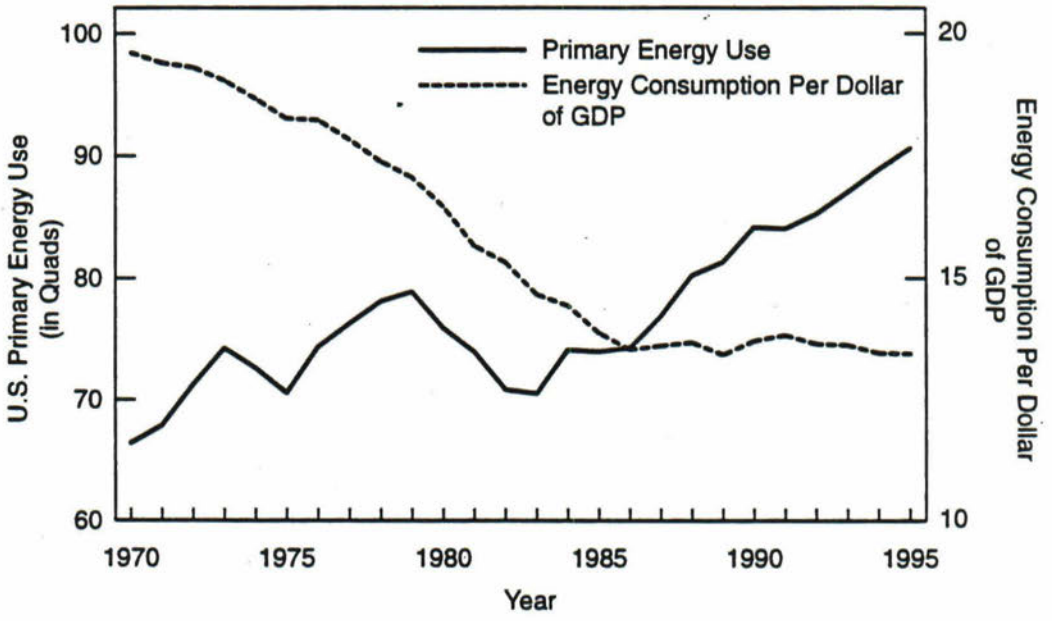
In studying historical trends in energy use and carbon emissions, we have chosen to highlight the years 1973, the beginning of rising energy prices to the nation; 1986, the year in which energy prices began a ten-year decline in real terms; 1990, the year generally used as a reference for carbon emissions; and 1997, the first year of our forecast period.

Between 1973 and 1986, the nation's consumption of primary energy froze at about 74 quads – while the GNP grew by 35%.[3] People purchased more fuel-efficient cars and appliances, insulated and caulked their homes, and adjusted thermostats. Businesses retrofitted their buildings with more efficient heating and cooling equipment and installed energy management and control systems. Factories adopted more efficient manufacturing processes and purchased more efficient motors for conveyors, pumps, fans, and compressors. These investments in more efficient technologies were facilitated by higher energy prices and by federal and state policies that were enacted and implemented to promote energy efficiency. About one-third of the freeze in energy use during this period was the result of structural changes such as declines in energy-intensive industry and increases in the service sector; two-thirds was due to increases in energy efficiency (DOE, 1995).

The gains in energy productivity achieved by the U.S. in the two decades following the 1973-74 Arab oil embargo represent one of the great economic success stories of this century. The extent to which the U.S. economy improved its energy productivity can be quantified by examining the relationship between total energy consumption and gross domestic product (GDP), as depicted in

Figure 2.1. In Figure 2.1, primary energy use is measured in quads and energy consumption per dollar of GDP is measured in thousands of Btus per 1992$. In 1970, 19.6 thousand Btu of energy were consumed for each dollar of GDP (1992$). By 1995, the energy intensity of the economy had dropped to 13.4 thousand Btu of energy per dollar of GDP (1992$) (EIA, 1996a, p. 17). DOE estimates that the country is saving $150 to $200 billion annually as a result of these improvements.

Figure 2.1 Energy Consumption Per Dollar of Gross Domestic Product: 1973-1995



Starting in 1986, energy prices began their descent in real terms that has continued to the present. As a result, energy demand grew from 74 quads in 1986 to 91 quads in 1995, and it continues to increase. One of the major lessons of the period since 1973 is that the economy will and can respond to energy price changes. In addition to prices, other factors are also important and can slow the decline in conservation activity that otherwise would be expected with declining energy prices. Federal policies, as well as federal, state, and utility programs and consumer preferences for energy-efficient appliances, houses, and cars can increase the purchase and use of energy-efficient products. Technological developments can improve the energy efficiency, reduce the carbon emissions, and often improve the performance of the product. Demand for energy-efficient products and low-carbon energy technologies is also strengthened by factors such as environmental concerns.

2.4.2 Sectoral Trends

Each end-use sector functions differently in the U.S. energy marketplace. One of the reasons for these differences is the differing market structure for delivering new technologies and products in each sector. Residential and commercial building technology is shaped by thousands of building contractors and architectural and engineering firms, whereas transportation technology is in the hands of a few manufacturers.

The principal causes of energy inefficiencies in manufacturing and transportation are not the same as the causes of inefficiencies in homes and office buildings, although there are some similarities (Hirst and Brown, 1990). For example, in the manufacturing sector, energy-efficiency investments

are hindered by a preference for investments that increase output compared with investments that reduce operating costs. The cost and relative difficulty of obtaining reliable information often prevents energy-efficient features of buildings from being capitalized into real estate prices. This is partly due to the lack of widely accepted building energy rating systems. These same information gaps do not characterize the transportation sector, which has a well understood labeling system for vehicles, in the form of miles per gallon. Misplaced incentives inhibit energy-efficient investments in each of the sectors. Consumers often must use the energy technologies selected by others. Specialists write product specifications for military purchases that limit access to alternatives. Fleet managers select the vehicles to be used by others. And architects, engineers, and builders have great control over the energy integrity of buildings, even though they do not pay the energy bills. The involvement of intermediaries in the purchase of energy technologies limits the ultimate consumer's role in decision making and leads to an emphasis on first cost rather than life-cycle cost (DOE, 1996b).

The end-use sectors also differ in terms of their ability to respond to changing energy prices. The transportation and residential sectors can respond relatively rapidly to price spikes, through reduced driving and by adjusting thermostat settings, respectively.

The vast differences in the R&D capability of the various sectors also influence their ability to respond quickly to changing energy prices and market signals. The private sector as a whole spends more than $110 billion per year on industrial R&D, dwarfing the federal expenditure on non-defense and non-space technology R&D (National Science Foundation, 1997). Of the private-sector R&D expenditure, the automobile manufacturers stand out – Ford alone spends more than $8 billion per year on R&D. Next comes the rest of the industrial sector. Here, manufacturers account for a majority of the R&D expenditures. Finally, in the buildings sector, the construction industry has virtually no indigenous R&D. The Council on Competitiveness in 1992 estimated that the construction industry spends less than 0.2% of its sales on R&D, far less than other industries, which average 3.5%.

Finally, each of the sectors is distinct in terms of their dynamics and primary societal benefits from improved energy efficiency. Improving the efficiency of transportation is needed to improve air quality and reduce dependence on imported oil. Improving the efficiency of the industrial sector improves economic competitiveness and is often effective in preventing pollution. Opportunities for energy-efficiency improvements are most widespread in the buildings sector because of market barriers in the form of information that is difficult to obtain, energy consumers who do not make purchase decisions on energy-using equipment, etc. Such differences make analysis by end-use sector essential for understanding the U.S. energy, carbon, and innovation picture as a whole.

Table 2.2 presents the primary energy consumed annually by the buildings, industry, and transportation sectors between 1973 and 1997. It shows significant sectoral differences in energy consumption trends. For instance, during the 1973-86 period when the country's primary energy use was steady at 74 quads, energy use in buildings and transportation increased by 2.7 quads and 2.2 quads respectively; industry experienced a compensating decline of 4.9 quads.

Over the entire period from 1973 to 1997, energy use increased in buildings from 24.1 to 33.7 quads (40%); in industry, from 31.5 to 32.6 quads (3.5%); and in transportation, from 18.6 to 25.5 quads (37%). As shown in Table 2.3, the growth in buildings and transportation has been relatively steady, at less than 1% per year from 1973 to 1986, and between 1.3 and 2.9% per year from 1986 to 1997. Growth in energy demand in industry has been much more volatile during the period, showing substantial declines during the period of rising prices (a negative 1.3% annual growth for the 13 years of increasing energy prices), an increase of 2.7% per year from 1986 to 1995, and a 2.9% per year decline from 1995 to 1997.

Table 2.2 Primary Energy Use in Quads: 1973-1997

	1973	1986	1990	1995	1997
Buildings	24.1	26.9	29.4	32.1	33.7
Industry	31.5	26.6	32.1	34.5	32.6
Transportation	18.6	20.8	22.6	24.1	25.5
Total	74.3	74.3	84.2	90.6	91.8

Source: Energy use estimates for 1973-95 come from EIA (1996a, Table 1.1, p. 39). Energy use estimates for 1997 come from EIA (1996c).

Table 2.3 Historical Energy Growth Rates: 1973-1997

	AAGR 1973-97	AAGR 1973-86	AAGR 1986-90	AAGR 1990-95	AAGR 1995-1997
Buildings	1.41%	0.85%	2.25%	1.77%	2.46%
Industry	0.14%	-1.31%	4.81%	1.45%	-2.87%
Transportation	1.32%	0.86%	2.10%	1.29%	2.86%
Total	0.89%	0.0%	3.18%	1.48%	0.66%

AAGR = Average Annual Growth Rate

The growth of carbon emissions during the period roughly follows that of energy demand growth. Table 2.4 shows estimated carbon emissions from 1973 to 1997. Like energy, carbon emissions were flat between 1973 and 1986. The increase in the fraction of coal in the final mix from 17.5% in 1973 to 23.2% in 1986 was offset by the increasing fraction of primary energy from nuclear power, from 0.1% in 1973 to 6.0% in 1986. From 1986 to 1997, carbon emissions grew more slowly than energy consumption. This was a result of an increase in the share of natural gas from 22.5% in 1987 to 25.4% in 1997 and in electricity from nuclear power from 4.5% to 7.2%, combined with a small decrease in coal (23.3% to 22.5%) and a larger decrease in petroleum (43.3% to 39.7%).

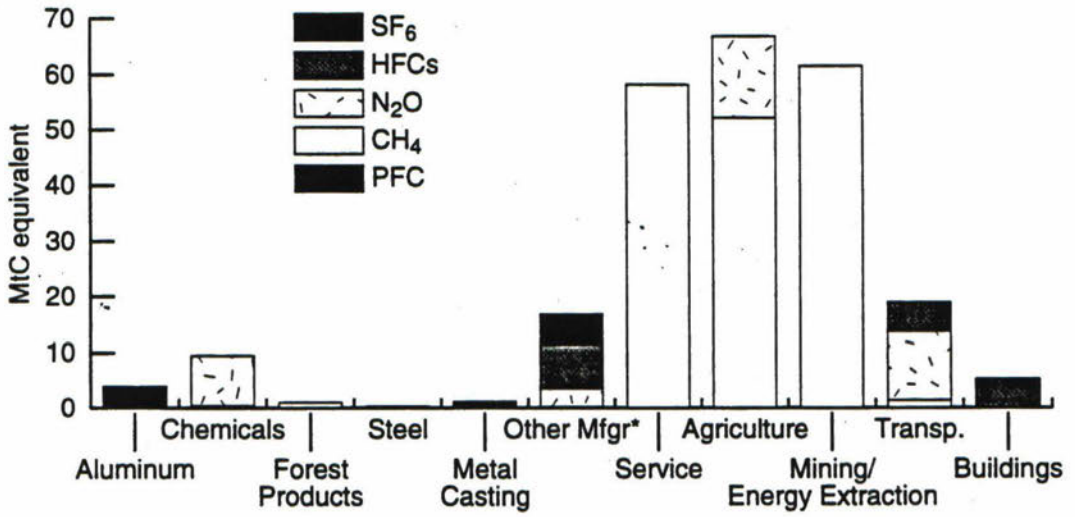
Table 2.4 Carbon Emissions from Fossil Energy Consumption: 1973 to 1997

	1973	1986	1990	1995	1997
Carbon emissions from energy in MtC	1260	1240	1344	1424	1480
	1973-97	**1973-86**	**1986-90**	**1990-95**	**1995-97**
Average annual growth rates (AAGR) for carbon emissions	0.67	–0.12%	2.03%	1.16%	1.95%

Sources: Carbon emissions estimates for 1990 are from EIA (1996b, Table 6, p. 16), and for 1995 are from EIA (1996b, Table A19, p. 120). Carbon emission estimates for 1973 and 1986 were derived using factors for carbon emissions from combustion of oil, natural gas, and coal for 1990. For 1997, they are from the end-use sector analyses described in Chapters 3 through 5 of this report.

Although non-CO_2 industrial emissions of greenhouse gases are small by weight, they have global warming potentials (GWPs) that range from 21 for methane to 23,900 for sulfur hexafloride (SF_6). Carbon dioxide has a GWP of one by definition. Figure 2.2 shows the relative contribution of these other gases in MtC equivalent. The largest non-CO_2 greenhouse gas contribution is from methane (CH_4), which is responsible for 177.5 MtC equivalent and has a GWP of 21. Next is nitrous oxide (N_2O), which is responsible for 39.1 MtC equivalent and has a GWP of 310. Finally, in 1994, various halocarbons and other engineered chemicals amounted to 29.5 MtC equivalent. These engineered chemicals are a source of concern since their emissions are growing rapidly – and the United States is the major source. SF_6 alone is increasing at a rate of 0.5 MtC equivalent per year (EIA 1996b). Note also that many of these emissions are seen not only in energy-intensive industries but also in "high-tech" and service industries, as shown in Figure 2.2.

Figure 2.2 Non-CO_2 Greenhouse Gas Emissions by End-Use Sector and Industry



* Mainly semiconductors

Source: EIA (1996b)

2.5 THE GOVERNMENT'S ROLE IN ENERGY R&D

2.5.1 Rationale for Government Support

Most people agree that the federal government has a clear and important role in the funding of basic research, and that it should not fund research that the private sector would conduct on its own. Between these two extremes is a wide range of applied technology development and deployment activities where the rationale for federal sponsorship is often unclear.

Economists have identified at least three situations in which the government's role in the R&D process is justified. First is the situation where the potential aggregate benefits of the research are large, but the uncertainties are simply too great for the private sector to shoulder the full research costs. Second is the case where R&D activities will result in benefits that cannot be captured by private entities. Although benefits might accrue to society at large, no single firm can realize enough economic gain to justify the research costs. A recent Council of Economic Advisors report

(CEA, 1995) estimated that the private returns from R&D are 20 to 30%, while social returns (including energy and environmental benefits) are 50% or higher. This economic barrier limits the extent to which the private sector can supplant a government role in maintaining nationally beneficial R&D. The third situation occurs when the public sector is the primary consumer of the results of the R&D. This is characteristic, for instance, of much defense and crime prevention research.

Based on these three justifications, the rationale for government support of energy-efficiency and low-carbon technology R&D is strong. Much of this research is both long-term and high-risk and therefore cannot be afforded by private companies despite the possibility of substantial gains in the long run. Examples include high temperature superconductivity, fuel cell vehicles, and building materials with switchable thermal and optical properties. Advances in energy research also offer substantial public benefits that cannot be fully captured by private entities. Specifically, energy-efficiency and low-carbon resources improve energy security by reducing the nation's reliance on foreign sources of oil; they lead to reductions in waste streams; and they reduce greenhouse gas emissions, which contribute to global warming. Finally, it is possible that governments will in the future become the principal purchaser of greenhouse gas reductions as the result of future international agreements. In this case, the third rationale for federal sponsorship of energy R&D will also apply.

Industry's R&D priorities are shifting away from basic and applied research and toward near-term product development and process enhancements. Business spending on applied research has dropped to 15% of overall company R&D spending, while basic research has dropped to just 2%. In addition, corporate investments in energy R&D, in particular, are down significantly (DOE, 1996a, p. 2).

Great potential exists for public-private R&D partnerships to produce scientific breakthroughs and incremental technology enhancements that will produce new and improved products for the marketplace. U.S. industry spends more than $100 billion per year on all types of R&D. The top 20 R&D performing companies all have R&D budgets exceeding $1 billion per year. These expenditures dwarf the U.S. government's energy-related R&D appropriations. If climate mitigation policies reoriented even a tiny fraction of this private-sector expenditure and capability, it could have an enormous impact. One way to reorient private-sector R&D is through industry-government R&D partnerships that involve joint technology roadmapping, collaborative priorities for the development of advanced energy-efficient and low-carbon technologies, and cost-shared R&D.

2.5.2 Past R&D Successes

Some indication of the cost-effectiveness of energy-efficiency R&D can be gleaned from the experiences to date of DOE's Office of Energy Efficiency and Renewable Energy. From fiscal year 1978 through fiscal year 1994, DOE spent a total of about $8 billion on energy-efficiency R&D and related deployment programs. Estimates of the benefits of several dozen projects supported by this funding were published in DOE/SEAB (1995). In response to a detailed review of these estimates by the General Accounting Office in 1995/96, DOE has revised and updated the estimated benefits accruing from five technologies that were developed with DOE support. Altogether, these five technologies alone have resulted in net benefits (i.e., the value of energy saved minus annualized cost premiums for better equipment) of approximately $28 billion (1996$) and annual emissions reductions of 16 MtC equivalent (Table 2.5).[4]

Thus, the value of the energy saved by these five technologies, alone, far exceeds the cost to the taxpayers of DOE's entire energy-efficiency R&D budget over the past two decades. Additional case studies and benefits are documented in Geller and McGaraghan (1996) and DOE/SEAB (1995).

Table 2.5 Cumulative Net Savings and Carbon Reductions from Five Energy-Efficient Technologies Developed with DOE Funding

Energy-Efficient Technology	Net Present Value of Savings Thru 1996 (billions of 1996$)	Annualized Consumer Cost Savings in 1996 (billions of 1996$)	Annual Carbon Reductions in 1996 (MtC equivalent)
• Building Design Software	11.0	0.5	8
• Refrigerator Compressor	6.0	0.7	3
• Electronic Ballast	3.7	1.4	1
• Flame Retention Head Oil Burner	5.0	0.5	3
• Low-Emissivity Windows	3.0	0.3	1
Totals	28	3.4	16

Note: Savings for the refrigerator compressor and flame retention head oil burner are through 1996 only; the remainder are savings from products in place by the end of 1996 and include estimated energy savings from the product's years in operation beyond 1996.

In addition to funding the development of numerous energy-efficient technologies, including those listed in Table 2.5, DOE has also developed and implemented energy-efficiency standards for equipment and building shells. For example, building efficiency standards became possible as a result of DOE's investment in "building design software" (the first line of Table 2.5). Because of a potential problem with "double-counting", Table 2.5 includes only energy savings achieved *beyond* the savings that resulted from the implementation of minimum energy-efficiency standards for buildings.

Moreover, results recently reported by Elliott et al. (1997) indicate that the total benefits – including both energy and non-energy savings – that accrue from so-called "energy-saving" projects in industry are typically much greater than those from the energy savings alone. In fact, based on numerous case studies, the authors conclude that the average total benefits received from these "energy-saving" projects are close to two to four times the value of the energy savings alone. They also noted that costs and benefits resulting from non-energy ramifications of energy-efficiency projects are often not included in cost/benefit analysis of energy-efficiency projects.

Similarly, Romm and Ervin (1996) describe some of the public health benefits that have resulted from advances in energy-efficient and renewable energy technologies, such as clean air and water. Other collateral benefits include the productivity gains that have accompanied investments in industrial efficiency improvements (Romm, 1994) and the growth in export markets for energy technologies.

2.6 REFERENCES

Arrow, Jorgenson, Krugman, Nordhaus, Solow, et al. 1997.

Council of Economic Advisors (CEA). 1995. *Supporting Research and Development to Promote Economic Growth: The Federal Government's Role* (Washington, DC: Council of Economic Advisors) October.

Elliott, R. N., S. Laitner, and M. Pye. 1997. "Considerations in the Estimation of Costs and Benefits of Industrial Energy Efficiency Projects", presented at the Thirty-Second Annual Intersociety Energy Conversion Engineering Congress, Honolulu, HI, July 27-August 1, Paper # 97-551.

Energy Information Administration (EIA). 1996a. *Annual Energy Review,* DOE/EIA-0384(95) (Washington, DC: U.S. Department of Energy), July.

Energy Information Administration (EIA). 1996b. *Emissions of Greenhouse Gases in the United States 1995.* DOE/EIA–0573(95). U.S. Department of Energy, Washington, D.C., October.

Energy Information Administration (EIA). 1996c. *Annual Energy Outlook 1997: With Projections to 2105,* DOE/EIA-0383(97) (Washington, DC: U.S. Department of Energy), December.

Geller, H., and S. McGaraghan. 1996. *Successful Government-Industry Partnership: The U.S. Department of Energy's Role in Advancing Energy-Efficient Technologies.* Washington, D.C.: American Council for an Energy Efficient Economy.

Hirst, E. and M. A. Brown. 1990. "Closing the Efficiency Gap: Barriers to the Efficient Use of Energy," *Resources, Conservation and Recycling,* 3: 267-281.

Intergovernmental Panel on Climate Change (IPCC). 1996. *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press), p. 5.

James, W. M. (The Procter and Gamble Company). 1997. Presentation at the AAAS S&T Policy Symposium, Washington, D.C., April 25.

National Academy of Sciences (NAS). 1992. *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base* (Washington, DC: National Academy Press).

Office of Technology Assessment (OTA). 1991. *Changing by Degrees: Steps to Reduce Greenhouse Gases,* OTA-0-482 (Washington, DC: U.S. Government Printing Office) February.

Romm, J. J. 1994. *Lean and Clean Management* (New York: Kodansha America Inc.).

Romm, J. J., and C. A. Ervin. 1996. "How Energy Policies Affect public Health," *Public Health Reports,* 5: 390-399.

U.S. Congress, Office of Technology Assessment. 1991. *Changing by Degrees: Steps to Reduce Greenhouse Gases,* OTA-0-482 (Washington, DC: U.S. Government Printing Office) February.

U.S. Department of Energy (DOE), Office of Policy. 1996a. *Corporate R&D in Transition.* (Washington, DC: U.S. Department of Energy), March.

U.S. Department of Energy (DOE), Office of Policy and International Affairs. 1996b. *Policies and Measures for Reducing Energy Related Greenhouse Gas Emissions.* DOE/PO–0047. U.S. Department of Energy. Washington, D.C., July.

U.S. Department of Energy (DOE). 1995. *Energy Conservation Trends,* DOE/PO-0034 (Washington, DC: U.S. Department of Energy, Office of Policy), April.

U.S. Department of Energy, Secretary of Energy Advisory Board (DOE/SEAB). 1995. *Task Force on Strategic Energy Research and Development, Annex* 3. (Washington, DC: U.S. Department of Energy), June.

ENDNOTES

[1] In this report, carbon dioxide is measured in carbon units, defined as the weight of the carbon content of carbon dioxide. Carbon dioxide units at full molecular weight (typically, million tonnes of carbon (MtC)) can be converted into carbon units by dividing by 44/12, or 3.67. This approach has been adopted for two reasons: (1) carbon dioxide is most commonly measured in carbon units in the scientific community, in part because it is argued that not all carbon from combustion is, in fact, emitted in the form of carbon dioxide, and (2) carbon units are more convenient for comparisons with data on fuel consumption and carbon sequestration (EIA, 1996b). Note that, in the U.S., a "ton" (sometimes referred to as a "short ton") equals 2000 pounds; a metric ton, or "tonne," equals 1000 kilograms (approximately 2204 pounds).

[2] We evaluate cost-effectiveness from several viewpoints, with real discounts between 7% and 20%. Even with the high discount rates, the efficiency case is cost-effective.

[3] Primary energy use is the chemical energy embodied in fossil fuels (coal, oil and natural gas) or biomass, the potential energy of a water reservoir, the electromagnetic energy of solar radiation, and the energy released in nuclear reactors. For the most part, primary energy is transformed into electricity or fuels such as gasoline, jet fuel, heating oil or charcoal – these, in turn, are referred to as secondary energy. The end-use sectors of the energy system provide energy services such as cooking, illumination, comfortable indoor climate, refrigerated storage, transportation and consumer goods using both primary and secondary energy (NAS, 1992, p. 3)

[4] The net present value (NPV) of cost savings, cumulative through 1996, is calculated as follows:

$$\text{NPV} = \sum_{t = \text{entry year}}^{\text{end of service}} \left(E_t - P_t\right) e^{0.07(1996 - t)}$$

where: E_t is the value in 1996$ of energy saved in year t

P_t is the annualized cost premium (1996$) of the better product

0.07 is the 7% real interest rate recommended by the Office of Management and Budget

Note that, for future years (1996 - t<0), $(E_t - P_t)$ is discounted by 7% per year; for past years, $(E_t - P_t)$ is raised 7% per year.

Chapter 3

THE BUILDINGS SECTOR

3.1 INTRODUCTION

Energy is used in buildings to provide a variety of services such as lighting, space heating and cooling, refrigeration, and electricity for electronics and other equipment. In the U.S., building energy consumption accounts for nearly one-third of total primary energy consumption and related greenhouse gas emissions. The cost of delivering all energy services in buildings (such as cold food, lighted offices, and warm homes) will be over $220 billion in 1997.

Our analysis shows that substantial reductions in future greenhouse gas emissions can be realized through the use of more energy-efficient technologies that save society money. In addition, these technologies often supply other benefits beyond energy, carbon, and dollar savings, including the following: (1) improved indoor environment, comfort, health, and safety, (2) reduced noise, (3) improved process control, and (4) increased amenity or convenience (Mills and Rosenfeld 1994). These indirect benefits, while difficult to quantify in economic terms, can be even more important than the energy cost savings, particularly when they improve the comfort of homeowners or the productivity of workers.

This chapter describes our detailed assessment of the achievable cost-effective potential for reducing carbon dioxide emissions in 2010.[1] We calculate carbon, energy, and dollar savings associated with adoption of more energy-efficient technologies. In addition, this chapter qualitatively describes the role of research and development (R&D) in providing a stream of advanced building technologies and practices after 2010 that will enable continued reduction in energy use and greenhouse gas emissions.

All costs in this chapter are reported in 1995 U.S. dollars (1995$). Carbon dioxide emissions are reported in terms of their carbon equivalent. To convert carbon dioxide units at full molecular weight into carbon units, divide by 44/12 or 3.67. For further information on emissions data, see EIA (1995).

3.2 PROVEN AND NEAR-TERM TECHNOLOGIES

In developing scenarios of carbon dioxide emissions for the residential and commercial buildings sectors, we drew from a wide range of information and models available on end-use energy demand, consumption, efficiencies, and technologies (see Section 3.7 References). Using this information, we developed a spreadsheet model that incorporates the work of existing models and analyses as parameters while providing a transparent framework to display assumptions, calculations, and results. This model, developed specifically for the project, is described in Appendix C-1.

3.2.1 Generic Assumptions

Our approach is based on a stock accounting framework of building and equipment types. For all scenarios, base case growth in households and commercial floorspace tracks historical trends. This results in a net total 2010 stock that is greater than 1997 levels by 15% and 12% in residential and commercial buildings, respectively, taking account of new building construction and retirement of existing stock. Retrofit or replacement of existing "shells" (walls, roofs, windows, doors) and

equipment is a function of their average lifetimes. We assume that, on average, residential and commercial building shells last 100 and 50 years, respectively, and thus only a small portion of buildings are replaced during the study period with a much larger fraction undergoing some shell retrofit. In contrast, average equipment lifetimes range from one year (for lights) to 20 years (for furnaces). All equipment with lifetimes significantly less than the forecast period (13 years), such as residential lighting, will be replaced but only a portion of the equipment with lifetimes comparable to or longer than the forecast period will be replaced. The combination of shell and equipment turnovers results in four categories of buildings in our model: (1) old buildings with old equipment; (2) old buildings with new equipment; (3) retrofit building shells with new equipment; and (4) new buildings with new equipment.

After characterizing the building stock in 2010, we calculate energy intensities (end-use energy per household or per unit floor area) for all end-uses for 1997 and, in our initial assessment, use the factors from the Energy Information Administration's (EIA's) *Annual Energy Outlook* (AEO97) to establish baseline values in 2010 (EIA, 1996). In general, average 2010 energy intensities are lower than those in 1997, reflecting technology improvements that provide the same level of energy service with less energy.

We multiply each equipment end-use energy in 1997 (e.g. water heating, cooling, lighting) in the four building categories by applicable energy intensities to derive future energy use. If more services per household or unit of commercial floorspace are required by consumers, or if the size of the overall building stock (relative to 1997) increases, this will increase the energy required to provide energy services. Thus, energy demand in 2010 is a product of the rates of change in energy service requirements within the buildings and changes in the overall growth in the building stock.

To derive energy-efficiency scenarios, we use the cost of energy intensity improvements and electricity and fuel prices in 2010 to assess cost-effective reductions in energy use. For the residential buildings, the efficiency scenarios also account for fuel switching (the impact of switching from electric to gas water heaters, clothes dryers, and ranges) and for the use of high-albedo roof materials ("cool roofs") to reduce cooling requirements (see Appendix C-4). For the commercial sector, we include the analysis of cool roofs but do not include fuel switching.

3.2.2 Scenario Definitions

The model was used to generate results for three scenarios: "business-as-usual" (BAU), "efficiency" (EFF), and "high-efficiency/low-carbon" (HE/LC). The business-as-usual scenario was calibrated to the National Energy Modeling System (NEMS) model outputs, so that it corresponds to the same 2010 baseline currently used in AEO97.

For both the efficiency and high-efficiency/low-carbon scenarios, we first calculate the 2010 energy use assuming 100% implementation of maximum cost-effective efficiency improvements in new building shells and equipment. This maximum efficiency potential was calculated as the difference between the energy intensity of the most cost-effective energy-efficiency technologies currently available, and the energy intensity of new equipment in 1997. The maximum cost-effective efficiency improvements are based on detailed studies; measures were not included if they had a cost of conserved energy greater than the average cost of purchased fuel or electricity.[2] For comparative purposes, we have also analyzed a "frozen efficiency case" in which the efficiencies of all new equipment and building shell measures are kept at 1997 levels of new products.

We then derive the efficiency scenario by assuming that 35% of the difference in total energy savings between the business-as-usual case and the maximum cost-effective efficiency case is achieved. For the high-efficiency/low-carbon scenario, we assume a 65% achievement rate. Assessments of future policy impacts are inherently speculative. We chose these implementation factors based on a review of program experience (Brown 1993, Brown 1994) and use of our judgment regarding how energy service markets would respond to policies and programs associated with aggressive commitments to reduce carbon emissions. We began with Brown's (1993) conclusion that about half of the techno-economic potential could be captured given coordinated efforts on minimum efficiency standards, utility programs, and information programs. Our choice of 35% and 65% brackets this result. The lower number (efficiency case) matches Brown's most pessimistic sensitivity case, while the higher number (high-efficiency/low-carbon case) corresponds to aggressive implementation of non-price policies combined with the assumption of policies such as a cap and trade system for carbon and other economic signals that would support these aggressive efforts. Brown did not address price signals in his report, so the most optimistic scenario he considers reaches about 60% of the maximum economic potential. We believe that the addition of these price signals under an aggressive policy regime is consistent with our assumption of an achievable efficiency level to 65%. Details of the scenario calculations are provided in Appendix C-2.

Emissions factors for fuel-fired end-uses are taken from EIA (1995), while electricity sector emissions factors are calculated in the utility section of this report. Electricity carbon emissions factors in the business-as-usual case are 163 gC/kWh of electricity at the meter. In the efficiency case, the marginal generating plants are high-efficiency gas-fired combined cycle plants, which reduces the carbon saved from each kWh to 95 gC/kWh. In the high-efficiency/low-carbon case, the carbon saved per kWh (relative to the business-as-usual case) increases to 127 gC/kWh because of changes in the electricity supply system brought about by the carbon permit price. (See Chapter 6, Tables 6.6 and 6.7, and accompanying discussion for an explanation of this factor.)

3.3 SCENARIOS FOR THE YEAR 2010

Three scenarios are presented for residential and commercial buildings carbon emissions in 2010: business-as-usual, efficiency, and high-efficiency/low-carbon. Tables 3.1 through 3.3 and Figure 3.1 provide the main results for the three scenarios.

On Figure 3.1, the x-axis shows the percent change in carbon emissions from 1990 levels. The y-axis shows total cost of energy services in 2010, expressed on an annual basis. This cost includes the annualized incremental cost of efficiency improvements beyond the business-as-usual case plus the cost of electricity and fuel purchases.

Table 3.1 Primary Energy Use in the Buildings Sector (quads): 1990-2010

End-Use/Fuel	1990	1997	2010		
			Business-as-Usual Case	Efficiency Case*	High-Efficiency/Low-Carbon Case*
Residential:					
Electricity	10.2	11.9	13.0	12.0 (7.1%)	10.8 (16.9%)
Fossil	6.5	7.2	7.4	7.3 (1.4%)	7.2 (2.6%)
Subtotal	16.7	19.1	20.4	19.4 (5.0%)	18.0 (11.8%)
Commercial:					
Electricity	9.4	10.6	11.4	10.7 (6.0%)	9.7 (14.9%)
Fossil Fuels	3.8	4.0	4.2	4.0 (4.7%)	3.9 (8.7%)
Subtotal	13.2	14.6	15.6	14.7 (5.6%)	13.5 (13.5%)
Sector Total:					
Electricity	19.7	22.5	24.3	22.7 (6.6%)	20.6 (15.2%)
Fossil	10.2	11.2	11.7	11.4 (2.6%)	11.1 (4.8%)
Total	29.9	33.7	36.0	34.1 (5.3%)	31.7 (11.9%)

* Numbers in parentheses represent percent reductions from the business-as-usual (BAU) case.

Note: Table does not include effects of building-sector fuel cells. Numbers may not add to the totals due to rounding.

Table 3.2 Carbon Emissions in the Buildings Sector (MtC): 1990-2010

End-Use/Fuel	1990	1997	2010		
			Business-as-Usual Case	Efficiency Case*	High-Efficiency/Low-Carbon Case*
Residential:					
Electricity	162	183	213	202 (5.4%)	185 (13.5%)**
Fossil Fuels	91	102	106	104 (1.5%)	102 (2.9%)
Subtotal	253	285	319	306 (4.1%)	287 (10.0%)
Commercial:					
Electricity	150	163	187	178 (4.7%)	165 (11.8%)**
Fossil Fuels	59	62	65	62 (4.5%)	59 (8.4%)
Subtotal	209	225	252	240 (4.7%)	225 (10.9%)
Sector Total:					
Electricity	312	346	401	380 (5.1%)	350 (12.7%)**
Fossil Fuels	150	164	170	166 (2.7%)	162 (5.0%)
Total	462	511	571	546 (4.4%)	511 (10.5%)

* Numbers in parentheses represent percent reductions from the business-as-usual (BAU) case.

** A portion of the reduction in carbon emissions associated with the high-efficiency/low-carbon case is due to changes in the electricity generation mix prompted by the charge of $50/tonne of carbon.

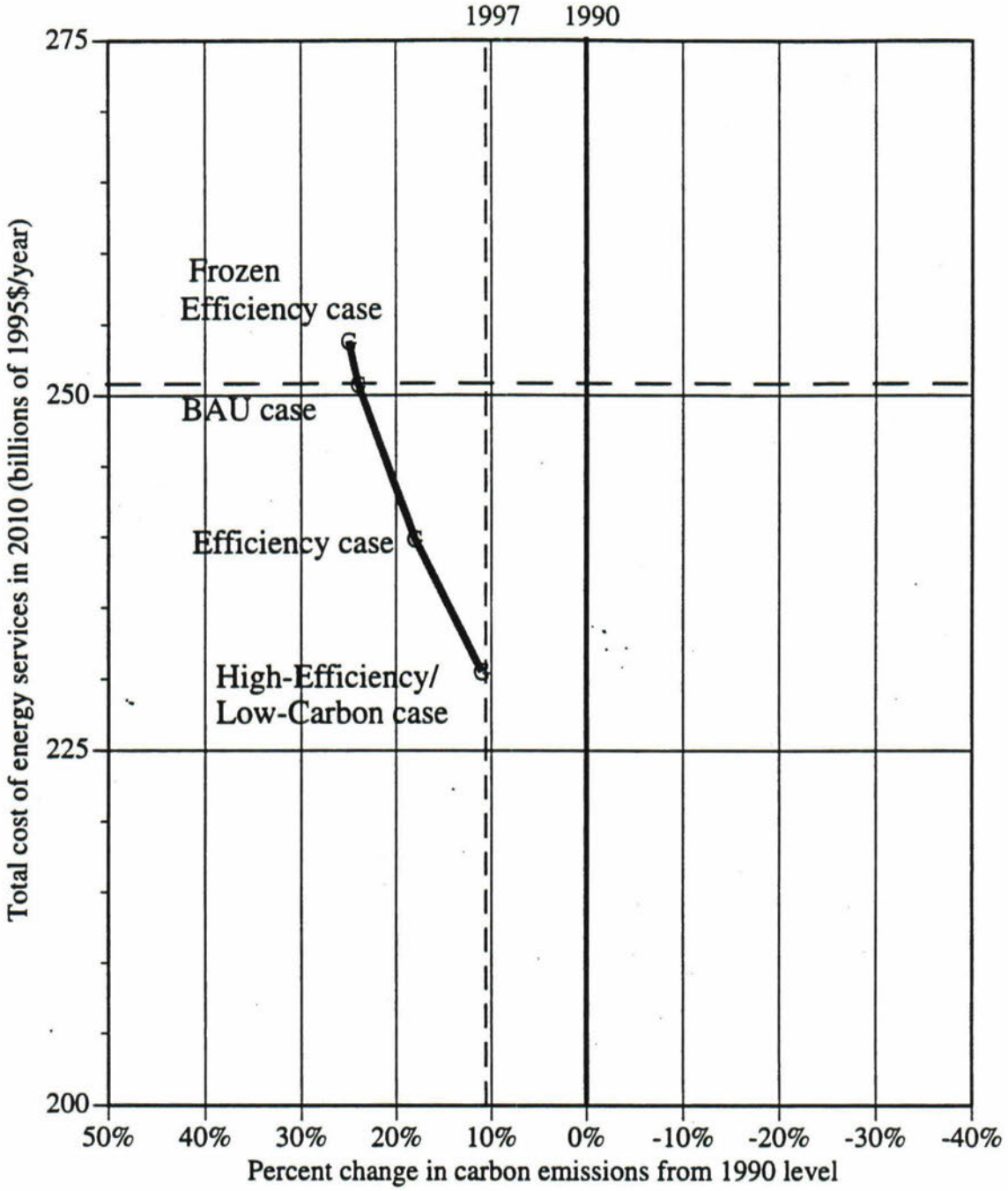
Note: Table does not include effects of building-sector fuel cells. Numbers may not add to the totals due to rounding.

Table 3.3 Annual Total Cost of Energy Services in the Buildings Sector (billions of 1995$): 1990-2010

	1990	1997	2010		
			Business-as-Usual Case	Efficiency Case	High-Efficiency/Low-Carbon Case
Annual Fuel Cost	$226	$228	$251	$233	$218
Annual Incremental Cost of Efficiency Improvement	--	--	$0	$7	$13
Annual Total Cost of Energy Services	$226	$228	$251	$240	$231

Note: All costs are expressed in 1995 dollars (1995$). The annual total cost of energy services equals the sum of annual fuel cost and annualized incremental cost of efficiency improvement (i.e., the cost of purchasing and operating higher-efficiency equipment in the efficiency and high-efficiency/low-carbon scenarios). Table does not include effects of building-sector fuel cells.

Figure 3.1 Relationship Between Costs of Energy Services and Carbon Emissions in the U.S. Buildings Sector in 2010



1990 U.S. buildings sector C emissions = 462 MtC

1997 U.S. buildings sector C emissions = 511 MtC

3.3.1 Business-as-Usual Scenario

The business-as-usual scenario provides an estimate of energy demand and carbon emissions in 2010 in the absence of any new efforts to promote the more rapid development, purchase, and use of high-efficiency technologies in the residential and commercial buildings sectors. In this scenario, energy demand grows by 20% from 1990 and 7% from 1997 levels (from 29.9 and 33.7 quads in 1990 and 1997, respectively, to 36.0 quads in 2010). Carbon emissions in 2010 are 24% and 12% higher than in 1990 and 1997, respectively (increasing from 462 MtC in 1990 and 511 MtC in 1997 to 571 MtC in 2010). Carbon emissions grow faster than primary energy use in the business-as-usual case, mainly reflecting changes in the fuel mix used to produce electricity. Because there is no accelerated efficiency improvement in the business-as-usual scenario, the total annual cost of energy services ($251 billion) is only the annual energy cost paid by consumers during that year.[3]

In the residential sector, energy use in the business-as-usual scenario grows from 16.7 quads in 1990 and 19.1 quads in 1997 to 20.4 quads in 2010, (a 22% and 7% increase over 1990 and 1997 levels, respectively). Carbon emissions are projected to grow from 253 MtC in 1990 and 285 MtC in 1997 to 319 MtC over the same time period (a 26% and 12% increase from 1990 and 1997, respectively). The increase in emissions in this sector is due to moderate growth in the residential building and equipment/appliance stock coupled with substantial growth in miscellaneous energy use. For analytical purposes, we divide these miscellaneous uses into three electricity categories (electronics, motors, and heating) and two non-electricity categories (natural gas and oil/other petroleum products).[4]

Emissions from the rise in miscellaneous electricity use grow nearly four times as fast as the residential sector as a whole, resulting in the share of miscellaneous electricity use jumping from 23% of total demand in 1997 to 29% in 2010. There exist important problems in the way that EIA defines and calculates the size of the miscellaneous end-use which leads to uncertainties in the correct values. It would be possible with more research to allocate some of the miscellaneous energy to the existing end-uses and to new ones; for example, electricity consumed by furnace fans should be treated as space heating. New end-uses for televisions and dishwashers might be appropriate. Even if the energy is not correctly allocated among the end-uses, the estimates of the savings potential will not significantly change. More research is needed to evaluate the amount of energy used for specific tasks as well as the technologies available to reduce energy use within the miscellaneous end-use category (for the most detailed recent assessments, see Sanchez (1997) and Koomey and Sanchez (1997)).

Despite these increases in service demand, total residential energy demand will be tempered through improvements in key residential equipment efficiencies, mainly due to implementation of appliance efficiency standards between 1997 and 2010. In particular, energy intensities for gas and electric water heaters, freezers, and refrigerators decrease by 34%, 29%, 18% and 15%, respectively, over the period. Had these declines in intensities not occurred, energy use for these end-uses would have been 14% greater in 2010 than the current business-as-usual scenario results. Residential sector energy use and carbon emissions in 1997 and 2010 are shown in Figure 3.2 below.

In the commercial sector, there are even greater problems in the way that EIA defines and calculates the size of the miscellaneous end-use than in the residential sector. Even given these accounting uncertainties, our assessment of the opportunities for efficiency improvements is almost certainly conservative.

In the commercial sector, energy use in the business-as-usual scenario is projected to grow by 18% from 1990 and 7% from 1997 to 2010 (13.2 quads in 1990 and 14.6 quads in 1997 to 15.6 quads in 2010). Carbon emissions are projected to grow by 21% from 1990 and 12% from 1997 to 2010 (209 MtC in 1990 and 225

MtC in 1997 to 252 MtC in 2010). Miscellaneous electricity end-uses such as motors, electronics, and small appliances are expected to increase from 9% of total commercial sector energy use in 1990 to 20% in 2010. This growth, which accounts for over 70% of the growth in carbon emissions in commercial buildings, offsets nearly all carbon emission reductions from energy-efficiency improvements in other end-uses. Miscellaneous energy use in the commercial sector is even less well understood than in the residential sector. As mentioned above, more analysis and data collection are needed to improve our understanding of this end-use category.

Although energy use from office equipment is expected to grow by 22% over the period, its share of energy use in commercial buildings remains relatively small, growing to 6% in 2010. The greatest increases in energy efficiency in the commercial sector come from continuing improvements in space conditioning (due to improved equipment and controls) and water heating systems. Commercial sector energy use and carbon emissions in 1997 and 2010 are shown in Figure 3.3 below.

Figure 3.2 Residential Sector Primary Energy Use and Carbon Emissions in 1997 and 2010 by End-Use for the Business-As-Usual Scenario[5]

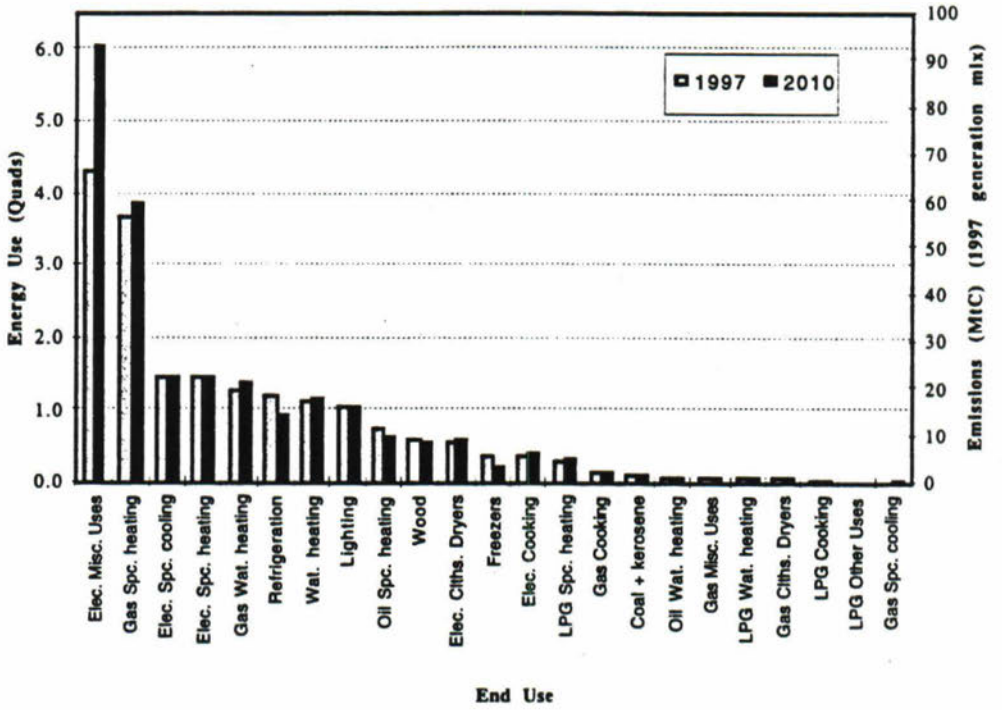
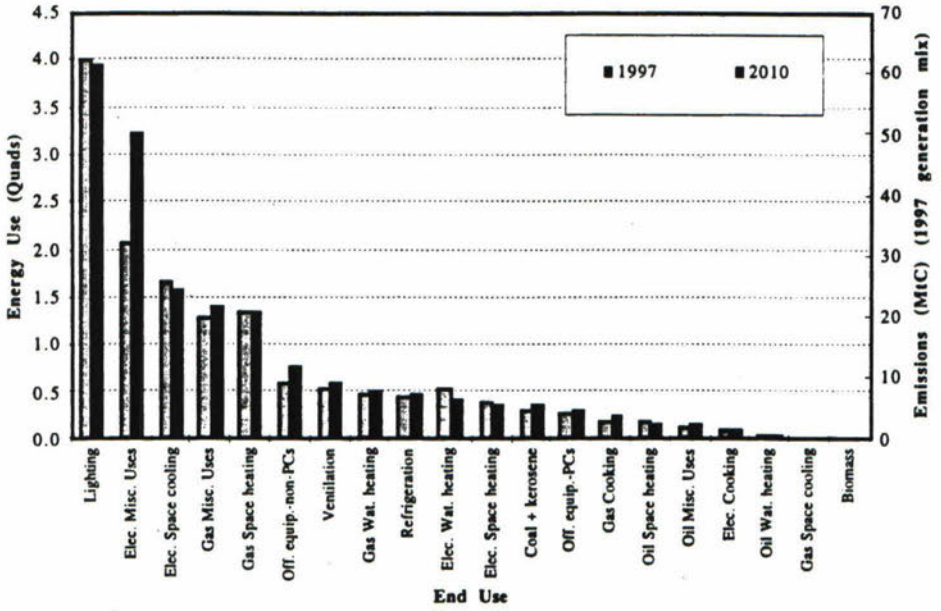


Figure 3.3 Commercial Sector Primary Energy Use and Carbon Emissions in 1997 and 2010 by End-Use for the Business-As-Usual Scenario



3.3.2 Maximum Cost-Effective Energy-Efficiency Potential

In determining the maximum cost-effective technical potential to be used as a baseline for development of the efficiency and high-efficiency/low-carbon scenarios, we reviewed and updated, as needed, the major recent sources of data on energy use and costs associated with upgrading to more efficient energy-using technologies. The results of this work, as well as the references on which it is based, are found in Appendix C-3. Once we determined the cost-effective energy-efficiency measures, we then used the energy use and incremental cost of new 1997 equipment for that end-use to calculate the potential efficiency improvement for that end-use. Table 3.4 lists the 1997 end-uses and their potential for energy intensity reductions when replaced by these highly energy-efficient technologies. As the table indicates, compared to 1997 new equipment, significant savings potential exists for many end-uses in the residential and commercial sectors.

The difference in energy demand between the maximum cost-effective case (100% of the potential) and the business-as-usual scenario for all buildings is 6.5 quads/year of primary energy in 2010. The efficiency and high-efficiency/low-carbon scenarios discussed below are based on the assumption that various shares of these savings are achieved.

Figures 3.4 and 3.5 show the percentage breakdown of savings for electricity and natural gas (these results are independent of the efficiency scenario because these scenarios vary only in the percentage of the maximum cost-effective resource assumed to be implemented, not in the character of that resource). More than 50% of the electricity savings is in "miscellaneous", and about a quarter is in lighting, with the remaining quarter split between space conditioning, water heating, and refrigeration. About half of the natural gas savings is in residential space heating, with commercial space conditioning and water heating splitting the remainder about equally.

Figure 3.6 shows a conservation supply curve for electricity savings in the high-efficiency/low-carbon case. This graph shows the electricity savings by end-use associated with the cost of achieving those savings. On the x-axis are the projected savings in 2010 in TWh, and on the y-axis is the cost of conserved electricity (CCE) in cents/kWh (1995$). Total savings in this scenario are about 16% of baseline electricity use. The most cost-effective savings come from commercial lighting, which has a negative net CCE because of the labor savings associated with replacing incandescent A-lamps with longer-lived halogen IR and compact fluorescent lamps. The costs of savings in other end-uses range from 1.4 to 4.5 cents/kWh.

Table 3.4 Cost-Effective Energy Savings Potentials for Selected End-Uses in the Residential and Commercial Buildings Sector*

End-Use	Energy Savings Potential: Retrofitted Shell/ New Equipment
Residential	
Fuel Switching - clothes drying**	59%
Lighting	53%
Miscellaneous electric end-uses	33%
Fuel Switching - Cooking**	33%
Refrigeration	33%
Fuel Switching - water heating**	29%
Electric water heating	28%
Freezers	28%
Electric space heating***	25%
Gas and oil water heating	23%
Electric space cooling***	16%
Gas space heating***	11%
Gas and oil cooking	15%
Miscellaneous gas and oil uses	10%
Commercial	
Space heating (electric and gas & oil)	48%
Space cooling (electric and gas)	48%
Ventilation	48%
Miscellaneous electric end-uses	33%
Refrigeration	31%
Lighting	25%
Electric water heating	20%
Gas and oil water heating	10%
Miscellaneous gas and oil end-uses	10%

* Energy savings potentials are calculated as the percent difference in energy intensity of maximum cost-effective technology and new 1997 technology. Savings are achieved using technologies listed in Appendix C-3. It is important to note that the impact these potentials have on reducing energy demand in the efficiency and high-efficiency/low-carbon scenarios depends not only on savings potential but also on the magnitude of energy demand by the particular end-use (see Tables in Appendix C-2) and the rate of turnover of equipment for that end-use.

** Fuel switching energy savings potentials reflect the unit energy savings in switching from electric clothes dryers, ranges, and water heaters to gas. Electricity energy is calculated as source energy using conversion factors from the utility chapter.

*** Energy savings potential for residential space conditioning is greater with new shells than with retrofitted shells. Our estimates for electric space heating, electric space cooling, and gas space heating with new shells show additional incremental savings of 14%, 7%, and 8%, respectively, beyond savings achieved with retrofitted shells.

Figure 3.4 End-Use Electricity Savings, 2010

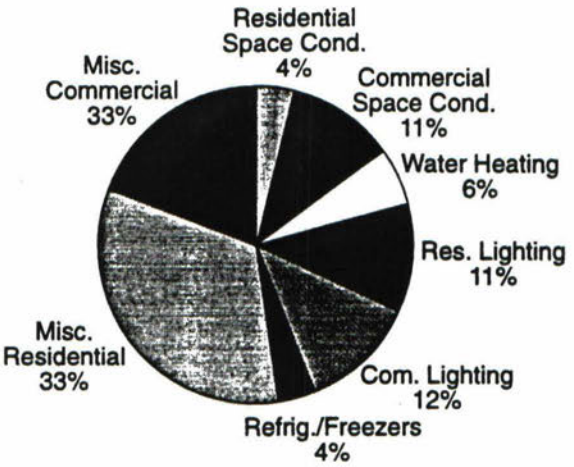
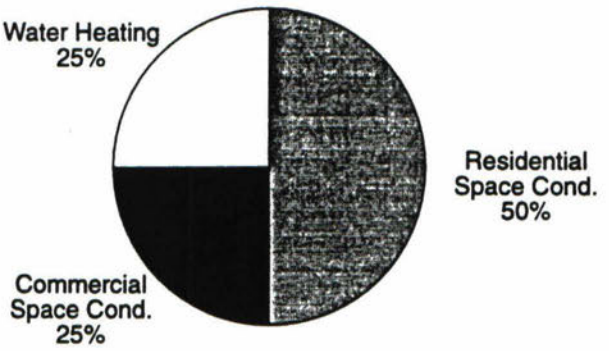


Figure 3.5 End-Use Natural Gas Savings, 2010



Note: The proportions of electricity and natural gas savings do not vary across scenarios. Total electricity savings in 2010 in the high-efficiency/low-carbon case are about 400 TWh, while total natural gas savings in this scenario are about 0.5 quads.

3.3.3 Efficiency Scenario Results

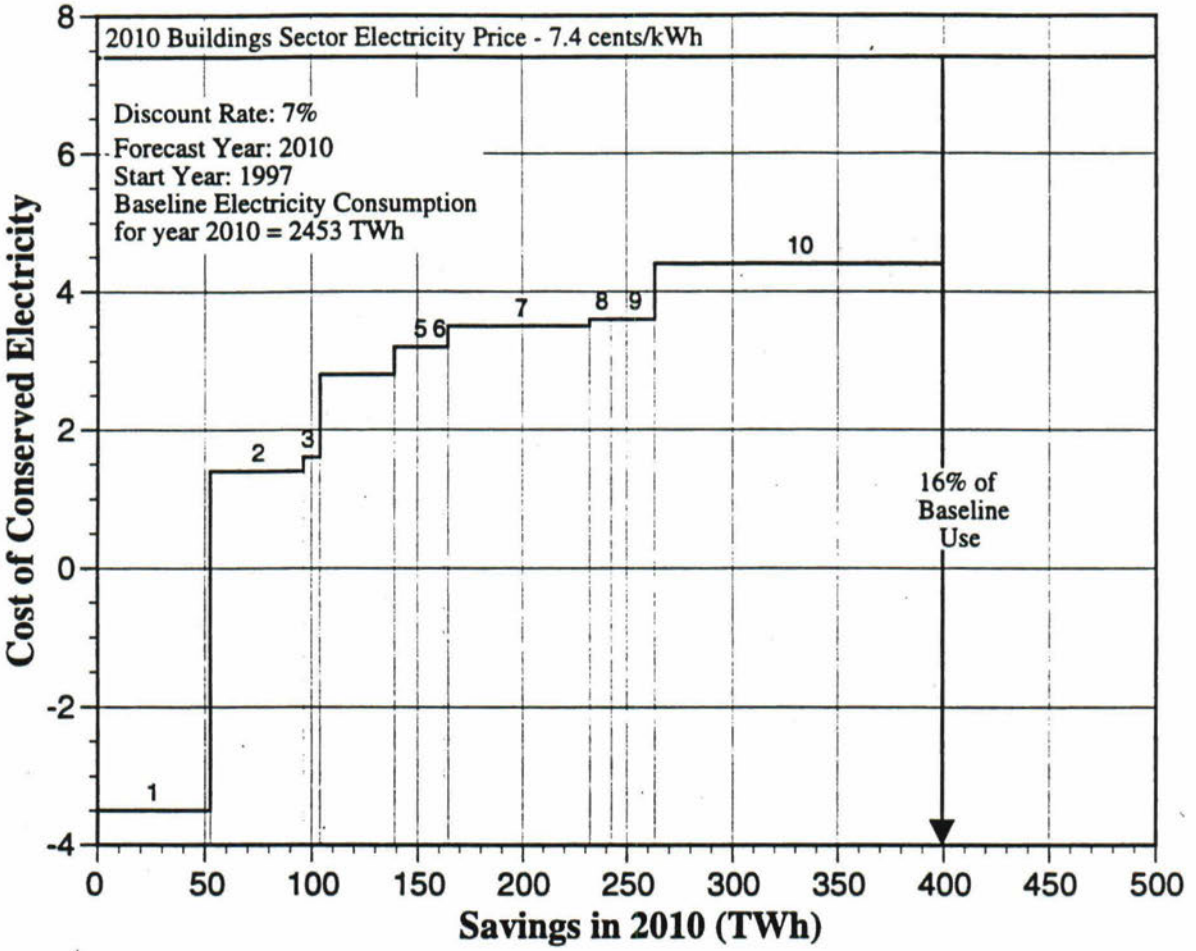
The efficiency scenario assumes that 35% of the maximum cost-effective efficiency savings are achieved by 2010. This assumption is based on expected savings resulting from a moderately vigorous effort to reduce energy use and carbon emissions using a combination of policy mechanisms that may include higher prices resulting from a cap and trade system, energy-efficiency standards, and information programs.

In the efficiency scenario, 2010 energy use drops to 34.1 quads while carbon emissions decline to 546 MtC. In this scenario, the total annual cost of energy services is $11 billion per year less than the annual energy services cost in the business-as-usual scenario, reflecting the fact that the decrease in energy expenditures resulting from more efficient technologies is greater than the increase in costs to purchase and install the technologies in residential and commercial buildings. The largest energy savings by end-use occur in miscellaneous electricity, lighting, water heating (residential) and space cooling (commercial).

3.3.4 High-Efficiency/Low-Carbon Scenario Results

The high-efficiency/low-carbon scenario assumes that 65% of the maximum cost-effective efficiency improvements are realized by 2010 as a result of a vigorous effort to reduce energy use and carbon emissions. In this scenario, 2010 energy use and carbon emissions drop further, to 31.6 quads and 512 MtC, respectively, at a total cost savings of $20 billion per year below the business-as-usual scenario. Annualized capital costs increase by $6 billion over the costs in the efficiency case, but annual additional bill savings are about $15 billion. Some of the carbon savings in the high efficiency/low-carbon case are associated with changes on the electricity supply side (see Chapter 6 for details).

Figure 3.6 Electricity Supply Curve By End-Use for Buildings in 2010, High-Efficiency/Low-Carbon Case



1 Commercial lighting
2 Commercial space conditioning
3 Commercial refrigeration
4 Residential lighting
5 Residential space conditioning
6 Commercial water heating
7 Commercial other uses
8 Residential refrigerators and freezers
9 Residential water heating
10 Residential other uses

Efficiency potential is calculated assuming 65% of technoeconomic potential is captured in the high-efficiency/low-carbon case. Savings from reflective roofing are contained in the residential and commercial space conditioning end-use categories.

Improving Efficiency and Saving Capital

Adding proven efficiency technologies to new homes can reduce monthly energy bills substantially. What is less well known is that clever design of new homes can also result in *capital cost credits* that can offset, in whole or in part, the additional capital costs of the more efficient technologies. For example, adding improved insulation and windows can allow a builder to reduce the size of the heating and cooling equipment and in some cases eliminate ductwork altogether. These credits can only be captured by builders who take a whole systems approach to design, but the benefits of such an approach are large, as shown by two real-world examples below.

Perry Bigelow, a builder in the Chicago area, has for years built highly energy-efficient homes that cost only $300 to $500 more to construct, in spite of his guarantee that these homes will have heating bills no higher than $200 annually (Andrews 1994). He accomplishes this goal by creating a well-insulated building envelope with little air leakage (taking care to provide appropriate levels of ventilation) and by replacing the furnace with a high-efficiency water heater that also doubles as the space heater. By using hydronic heating, he can save $1000 on ductwork. He also can downsize the air conditioner because the home's cooling load is so much lower than typical practice, saving another $80 to $100. These savings totally offset the cost of the added insulation and the air sealing, leaving a small additional cost to pay for low-emissivity gas filled windows and fluorescent lighting.

Builder Barbara Harwood, whose company is based in Carrollton, Texas, built a block of homes in Dallas called Esperanza Del Sol (Schwolsky 1997). The homes are small (1273 square feet) and inexpensive ($80,000), but are so efficient that Harwood can guarantee that heating and cooling costs will be no more than $1/day ($365/year). She upgraded insulation levels, reduced air infiltration, and added an active ventilation system. To offset these costs, she used a smaller-capacity geothermal heat pump and redesigned the ductwork. With these offsetting cost credits, the more efficient homes cost only $150 more than their inefficient counterparts, but save about $40/month in energy bills. The consumer who purchases these homes would have to pay another $1.10/month on an 8%, 30 year mortgage to finance the added capital cost; the monthly energy savings are almost 40 times larger, providing immediate positive cash flow to the homeowner.

These builders have discovered the benefits of an integrated design approach. They both use the "hook" of guaranteed maximum energy bills to market efficiency to customers who might otherwise be reluctant to spend more for it. They have shown that, with correct sizing of equipment and clever redesign of building systems, highly efficient homes need only cost a little more up-front.

Commercial buildings can also benefit from HVAC equipment downsizing. Pacific Gas and Electric Company's Advanced Customer Technology Test for maximum energy efficiency (ACT^2) had one pilot project in San Ramon, California (Houghton et al. 1992). This 20,000 square foot office building was retrofit using improved glazing, more efficient lighting, and better controlled HVAC systems. Chiller capacity was reduced by more than 40% because of better solar control from the windows and the reduced internal loads from lighting. The savings from the smaller chiller offset some of the cost of the window and lighting retrofits.

3.4 POTENTIAL FOR ADVANCED TECHNOLOGIES IN 2020[6]

To the casual observer, buildings in the year 2020 may look much like the buildings of today (Smith and Rivera, 1989). This is because Americans prefer familiar forms for their buildings and because new buildings amount to only 2-3% of the existing building stock in any given year. Nearly 90% of the residential buildings, and 80% of the commercial buildings, that existed in 1997 will still be occupied in 2010. By 2020, significantly more than half of the 1990 stock will still be in service.

However, beneath the surface, many significant changes are expected to occur that will affect how buildings are constructed, the materials and systems used to build them, and the way in which buildings are maintained and used (Smith and Rivera, 1989; Wendt, 1994). Without a sustained and vigorous public-private research, development, and demonstration (RD&D) partnership, these changes could lead to only modest improvements in energy efficiency. In contrast, an invigorated buildings RD&D scenario over the next 25 years offers the potential to produce breakthrough technologies that could dramatically reduce the energy requirements and environmental impacts of buildings, while enhancing affordability, long-term durability, resistance to disasters, and indoor environmental quality.

For advanced energy-efficiency technologies to penetrate the buildings industry by the year 2020, they will have to be cost-effective, and passing the cost-effectiveness hurdle will be challenged by energy prices that could decrease well into the 21st century. Thus, incorporation of additional features to make energy-efficient technologies more attractive to consumers will be needed to ensure success in the marketplace and should be part of the R&D planning process. RD&D will also be instrumental in capturing the potential of existing technologies by establishing better programming, design, and commissioning practices for buildings (Todesco 1996). Further, investments in training and education will be required to enable technicians and engineers to keep pace with a new generation of technologies and practices. New construction techniques, novel heating systems, electronic appliance tuning and control, more sophisticated building wiring practices, and the field installation of factory-built housing all require new talents for those who build, maintain, and service buildings. There must also be a concerted effort to facilitate the integration of new technologies.

This section identifies the potential improvements to energy-efficiency technologies that could result by 2020 given a sufficiently vigorous R&D effort. Savings discussed here would be in addition to savings estimated in the quantitative analysis for 2010 above.

3.4.1 New Technologies and Practices

Many of the changes in building technologies occurring over the next 25 years will be evolutionary in nature, resulting from ongoing research that is continuously providing solutions to such issues as moisture damage in structures, anomalous heat losses from envelopes, and indoor air quality problems. By 2020, these solutions will have evolved into cost-effective practices and products that will be the norm in new and existing buildings. In addition, a sustained, vigorous program of public and private-sector RD&D could produce many novel building technologies and practices by the year 2020. The following six areas offer great promise to significantly reduce the energy requirements of our nation's buildings through a combination of incremental and aggressive technology improvements:

- Advanced construction methods and materials;
- Environmental integration and adaptive envelopes;

- Multi-functional equipment and integrated system design;
- Advanced lighting systems;
- Controls, communications, and measurement; and
- Self-powered buildings.

In each area, thought must be given not only to energy-efficient technologies and energy costs, but also to the incorporation of other beneficial non-energy features that will accelerate their introduction into the marketplace, such as lower first costs, ease of integration, time savings, durability, comfort, and improved indoor environments.

3.4.1.1 Advanced Construction Methods and Materials

With sufficient RD&D support over the next 25 years, a systems engineering approach to the building's life-cycle (programming, design, construction, commissioning, financing, operation, renovation, reuse, and disposal) could become the norm. Such a transformation offers the potential to deliver buildings with lower total first costs and lower energy consumption, as well as higher overall quality and faster construction (Lawson, 1996; Lovins, 1992). The lower total first costs will permit the reinvestment of some capital savings into additional cost-effective, energy-efficient technologies. The total reduction in energy use could thereby be considerable.

By the year 2020, on-site labor for single-family homes, low-rise multi-family construction, and commercial buildings of standard design (e.g., franchise restaurants and retail stores) will consist primarily of assembling manufactured components and installing complete modules. This shift will require less skilled, and more semi-skilled, on-site labor. The expanded use of CAD/CAM technologies could enable "mass customization" capabilities, permitting the manufacture of virtually all residences and many commercial buildings. Quality and material improvements that are not affordable on a one-of-a-kind basis, can be assimilated into the high-volume manufacturing process. Continued research into the manufacture of building components is needed to enable these changes, to reduce waste, and to facilitate the recycling of unused materials.

Advanced modular construction methods will result in attractive, affordable, and flexible buildings that will permit longer occupancy in homes, offices, and other commercial buildings. Modular and easily installed heating, ventilating, and air-conditioning (HVAC) units with improved, leak-free, insulated ducting will reduce installation and operation costs. By extending the average length of stay in buildings, life-cycle costs become more important to decision makers. Durability and the need for reusable and recyclable materials will therefore increase in importance, generating the need for better durability testing tools and advances in materials, systems, and assemblies (Darrow, 1994). Better "engineered" wood, stress skin panels, optimized light-weight steel components, and adhesive assembly techniques will be needed. Greater use of recycled materials requires the development of higher "value added" uses for current wastes and the invention of low-value recycled products. Examples being developed today include the following: (1) mixed paper waste in lieu of pure newsprint to cellulose insulation and drywall; (2) wood wastes to engineered structural members as opposed to only particle board; (3) flyash to lightweight masonry products as opposed to site fill material; (4) corrugated paper to structural insulating panels; and (5) plastics to carpeting and wood/plastic composites. The recycled materials must also be low- or non-emitting materials in order to meet consumer concerns about indoor air quality. A program of vigorous materials research could make these new materials commonplace by 2020.

By 2020, building life-cycle information management systems will create efficiency in the architectural/engineering/construction process and in building operations. Information systems will facilitate communication of programming and design intent through construction, commissioning, maintenance, and operation of buildings. Performance tracking will insure persistence of savings from efficient design and equipment. And, most significantly, continuous improvement in buildings will occur through feedback of performance information to design of new buildings and renovations.

Over the next quarter century, there will be greater use of computer software in every aspect of the building life-cycle. Design tools and building simulators will be more powerful and easier to use, with improved graphical interfaces and links to manufacturer databases of equipment specifications. There will be construction management and commissioning software for use in all stages of a building's life-cycle including early design and commissioning. This software will be used to create calibrated computer models to verify that actual building performance meets pre-specified design targets that could be part of a performance contract. The calibrated model could have many uses in operations and maintenance, including assisting in evaluation of the least-cost energy supplies, optimization of existing control strategies, and analysis of possible retrofit options. Finally, such data on actual as-operated conditions close the feedback loop that is problematic today. Building designers will finally have an opportunity to learn how buildings they design actually perform, and their future designs will benefit from lessons they learn based on existing buildings.

3.4.1.2 Environmental Integration and Adaptive Envelopes

Advanced designs and technologies that intelligently integrate the performance of buildings with the outdoor environment offer the potential to more efficiently heat, cool, insulate, ventilate, and illuminate interior spaces. A variety of building designs tailored to the wide range of climates in the U.S. will reduce first costs and operating costs. Equipped with these climate-specific and smart technologies, the word "shelter" will no longer imply the exclusion of outdoor elements; instead it will refer to structures that capitalize on fluctuating outside conditions to create interior comfort and light.

One of the most significant changes in envelope performance from 1970 to 1995 was the development of a new generation of window technology that involved high-transmittance low-emissivity (low-E) glazings; the introduction of this new window technology resulted in a major shift in the window marketplace. By 2020, the market penetration of such technologies could double as high-rate, thin-film coating techniques make it possible to coat glass and plastic for cost-effective use in virtually every climate. New types of highly insulating glazings (such as aerogel and honeycomb) will compete for new markets if materials research is able to produce a window that, by enabling the diffuse solar gain to exceed the winter thermal losses, outperforms a highly insulated wall even on northern exposures in winter.

In most larger commercial buildings and in sunbelt housing, control of solar gain is critical. Since building needs vary widely and climatic variables are unpredictable, one ideal component would be a dynamically controllable "smart glass". The fundamental materials science technology base for "active" and "passive" smart glazing technologies such as electrochromic coatings was developed in the 1990s. However, RD&D resources are needed to develop viable and cost-effective materials with optical properties that can be switched passively. In addition, research on switching mechanisms is needed to assess the potential applicability of the range of alternatives, including short wavelength switching to a reflective mode and long wavelength switching for thermal comfort (Kammerud, 1995).[7]

To date, research on insulation has focused on static insulation systems, where insulation is simply put in place to increase the thermal resistance of the roof, wall, or floor by a fixed amount. An alternative is to consider dynamic systems, in which the performance of the building envelope changes with the environment to minimize the building energy load. One study (Fine and McElroy 1989) found that dynamic building envelope systems (insulation, roofs, walls, and windows) could reduce heating and cooling loads by 20 to 35%. Adaptive envelopes should be developed which integrate other useful features, such as ventilation air intakes with heat exchangers and sensors that are engineered as an integral part of the envelope, or energy-efficient windows as part of a unit.

Better use of thermal storage concepts would increase the ability of passive solar heating and cooling to offset the use of mechanical systems. One possibility is to distribute natural heating and cooling more uniformly over the day with resultant decreases in both heating and cooling requirements. Development of phase-change materials with storage capacity and release rates adapted to building use is needed. Applied R&D is needed to make such materials economically competitive with standard building products, and to demonstrate their durability and safety. In addition, to achieve the technical potential of these thermal mass strategies, design and construction guidance is needed to identify how mass and insulation should be rearranged to optimize thermal storage effects in specific climate regions (Christian, 1991).

Self-drying roof concepts are under development, and their commercialization offers significant cost and energy benefits. Behind this work is the notion that roofs should be designed to accommodate occasional leaks; that is, there should be a means to dry out the roof and restore it to its original thermal performance after a leak is patched. One promising technique is to design roofs that dry to the interior through evaporation. By extending roof life, self-drying promotes the installation of better insulation, since the originally installed insulation will remain in place longer. In addition to reducing energy loss, self-drying roofs also significantly reduce the cost of repairing, replacing, and disposing of roofs.

The success of environmentally adaptive envelopes depends upon improved design and commissioning practice, the development of advanced manufacturing techniques, new materials, and sensor and control technologies to produce customized wall, roof, and floor panels that meet the needs of buildings in different climates. Other important properties and features should be simultaneously sought in the development of new materials such as reduced maintenance, resistance to water condensation, and low emissions. Research is also needed to integrate the dynamics of such advanced envelopes into total building energy management systems.

Mitigating Urban Heat Islands With Cool Roofs And Trees

The benefits of reducing urban heat islands through reflective roofing, white pavements, and tree planting have gained increasing attention in recent years (Rosenfeld et al. 1996 and 1997, Konopacki et al. 1997). These savings are both from the direct effect of sunlight being reflected (by white roofs) or blocked (by trees) and hence prevented from entering the building envelope, and from the indirect effect of cooler ambient conditions brought about by evapotranspiration from trees and increased albedo. The cooler ambient conditions have the additional benefit of reducing smog formation (which is directly related to air temperature).

The calculations above include estimates of savings from the direct and indirect effects of cool roofing on building energy use but do not include the potential effects of large-scale tree planting. In the efficiency case in 2010, cool roofs save about 4 TWh of cooling electricity, while increasing heating gas use by 0.01 quads. In the high-efficiency/low-carbon case in 2010, cool roofs save about 8 TWh of cooling electricity (worth more than $500 million per year), while increasing heating gas use by 0.02 quads (worth more than $100 million per year). The associated net carbon savings (after subtracting out the penalty for the increased heating gas use) are 0.2 MtC in the efficiency case and 1.3 MtC in the high-efficiency/low-carbon case. The cost of these reductions are negligible, because changing roofing materials to be more reflective at the manufacturing stage is generally a zero cost option. The development of advanced roofing, paving, and coating technologies would improve the longevity and economics of these cool community options.

The additional savings from tree planting have not been included in the calculations, but the direct and indirect effects from trees are generally of the same order of magnitude as for cool roofs (Rosenfeld et al. 1996). The total savings from cool roofs and trees together would therefore be on the order of 2-3 MtC in the high-efficiency/low-carbon case by 2010.

The cost of tree planting is more difficult to estimate, because of the sizeable unquantifiable benefits of trees, as well as the long-term maintenance costs. Most people regard trees as a net positive contribution to their local environment, and it is likely that the overall benefits (including the energy and carbon savings benefits) substantially exceed the costs, but because of the uncertainties in estimating these costs, we did not include tree planting in our savings estimates.

3.4.1.3 Multi-Functional Equipment and Integrated System Design

During the period through 2010, the efficiencies of HVAC equipment, water heating and other appliances will continue to increase through incremental improvements. Efficiency improvements will probably continue to be driven both by minimum efficiency standards as well as by marketplace competition for technologies that have low operating costs because they are efficient. In many cases, however, appliance and equipment efficiencies are reaching either their thermodynamic limits, or can be made higher only at significantly higher first cost.[8] For example, electric resistance water heaters have become more than 90% efficient with 100% as the maximum. Gas water heaters and refrigerators provide other examples where efficiencies may be reaching either an economic or thermal limit. Condensing gas water heaters that have efficiencies above 90% have been developed, but are generally too expensive for a mass market. In the case of refrigerators, applied research and development has recently produced a 20 cubic foot refrigerator which consumes no more electricity than a 40-watt light bulb running continuously (350 kWh/year). We anticipate that the technologies used to reach this performance level will be available to the U.S. refrigerator market in the next decade. To move refrigerators, as single-function appliances, beyond this level of performance does not appear to be cost-effective in the near-term or beyond if real energy prices continue to decrease.

Opportunities continue to exist for reducing losses in poorly designed hot water storage and distribution systems. Improved tank/flue designs, improved piping layout and design, and advanced circulation systems are some of the possibilities.

Based on the limits to performance for single-function equipment such as refrigerators, water heaters, and HVAC equipment, RD&D efforts need to focus on multi-functional equipment and appliances to provide the next quantum jump in efficiency improvement. Multi-functional equipment needs to be developed that combines and integrates the functions of several appliances into a single, highly efficient device. Such equipment promises to be highly efficient because the heating and cooling that is rejected by a single-function device can be put to use in the integrated appliance, and the component with the highest efficiency can be used to provide a dual function.

An example of multi-functional equipment is an integrated water heating/space conditioning system which uses heat pumping to meet space heating, air conditioning, and water heating loads. As a combined, integrated appliance, this unit's efficiency (as measured by the Seasonal Energy Efficiency Ratio, or SEER) could be a full 70% higher than the combined efficiency of today's central air-conditioning system and water heating system. Energy-efficient air filtration, as well as humidity and temperature control, could be incorporated into HVAC systems to reduce indoor concentrations of airborne particles such as pollen, other allergens, and infectious agents that cause adverse health effects. This type of integrated technology can be applied to residential as well as commercial buildings. As the efficiency of a single-function device is improved through incremental development, as part of an integrated approach, this device is able to provide still higher efficiencies.

There is also a large opportunity for integrated products that can control space humidity and temperature independent of each other. Research on combined systems that use desiccants to control humidity and vapor compression air conditioning to control temperature is expected to result in an efficient, integrated system that can provide better comfort at reduced operating costs.

Further opportunities exist for improving the efficiency of heating and cooling systems in buildings through integrated systems design, right sizing, modular/multiple equipment configurations, and better integration of the process for distributing space heating and cooling within buildings (Shepard 1995). As air conditioning and chiller efficiencies continue to improve with cascade, multi-stage, and turbine-assisted compressors, the energy consumption and electrical demand associated with oversizing, poor part-load performance, and the distribution of air and water becomes a greater fraction of the total HVAC energy use in both residential and commercial buildings. Research on load diversity, system integration, and design paradigms can reduce both peak demand and energy use. In addition, research on advanced thermal distribution technologies could enable the development and commercialization of higher-efficiency, quieter thermal distribution systems, with air filtration to improve indoor air quality. At a higher level, integrating heating/cooling devices as part of the distribution system itself, along with improved integration of task/local environmental control systems, would provide efficiency benefits and enable use of control technologies to target heating and cooling within a building.

There are other options for appliance integration, including combining water heating with dehumidification, mechanical ventilation, and/or refrigeration. In these cases, heating or cooling is produced for multiple applications and at much higher efficiency than would otherwise be possible. In the 2000 - 2010 time period, research in fields of heat transfer, controls, component technology development, and systems analysis will need to be conducted so that industry can take these results and apply them to developing integrated products for both residential and commercial buildings. By 2020, we anticipate that efficient integrated and multi-function products could capture a substantial fraction of the U.S. market for space conditioning, ventilation, water heating, and refrigeration.

3.4.1.4 Advanced Lighting Systems

Lighting is a dominant energy end-use in the commercial sector, an important use in houses, and an essential element of roadway and outdoor use. At the national level, lighting accounts for 23% of all U.S. electrical energy use. Through the development and intelligent use of more efficient lighting technologies and design, lighting energy use could be reduced by over 50% by 2020 with equal or improved health, comfort and productivity.

Lighting use is characterized by a tremendous diversity of applications and needs, and an equivalent diversity of sources, fixtures, controls, and designs. Thus, energy efficiency can best be achieved by an array of new and existing technologies intelligently matched to the appropriate lighting needs. Unlike other aspects of the building infrastructure, most lighting system components are replaced at a relatively high turnover rate within ten years, and thus provide opportunities to introduce more efficient technologies on a regular basis. At the national scale, we spend $10 billion/year for new lighting equipment but $40 billion/year for lighting energy consumption. By 2020, we must make a transition to investing more each year in improved technology with the benefit of dropping the annual consumption figure by 50%.

Changing the overall efficiency of U. S. lighting use can be viewed as improving four efficiency parameters: (1) lamp or ballast efficacy, (2) fixture efficiency, (3) spatial task efficiency, and (4) temporal control efficiency. There are large opportunities for improvements in each of these areas:

Lamp efficacies for fluorescent and other gas discharge sources have improved modestly over the last 20 years, but are still well below the theoretical limit. The industry is exploring new electrodeless solutions in both small sizes (10-100 watts) and in the kilowatt range. Large lamps, such as the sulfur lamp, have demonstrated higher performance in prototype form. Some technologies have other advantages, such as reduced maintenance due to long operating life, or better environmental properties (e.g., mercury-free lamps). Most of the new discharge sources will benefit from continued development of less expensive, smaller, and more efficient electronic power supplies. Dimmability will also be more readily achievable using these new power supplies. Light sources that use phosphors may be further improved by advances in the chemistry of phosphors.

By 2020, there will be many new CFL options with smaller size, better color rendition, higher luminous output, and dimmability. But there will still be a tremendous market need for a long life, very low cost, incandescent lamp replacement, perhaps utilizing improved filament technology or halogen lamps with IR reflecting coatings. Finally, there are other contenders for the small source market such as mini-HID sources and solid state light sources (LEDs or laser diodes).

There will be continued improvement in fixture design for both direct and indirect lighting systems so that a greater fraction of the light is usefully extracted from the source, using innovations in highly reflecting surfaces, refractive and diffracting materials, and non-imaging optical designs. Two seemingly contradictory trends will continue through 2020. One trend will be towards localized lighting that provides just the lighting needed at each task location and is flexible enough to adapt to the ever-changing needs of today's office and factory environments. The other trend is towards the use of centralized lighting in situations that require uniform light levels on a fixed schedule over long periods of time. Hollow light guides and light pipes must be developed to meet these needs and fiber optic designs can be used for smaller-scale centralized solutions.

Lighting controls have only recently advanced beyond simple on-off, multi-level, or time clock controls to occupancy-based controls and photosensor controls that respond to daylight and lumen maintenance. By 2020, new generations of smart control systems will respond automatically to changing task and environmental needs. Voice-activated controls and flexible linkages (wired and

wireless) between light sources and tasks will provide new flexibility in both office and retail environments. Controls linked to dimmable lighting systems and to building energy management control systems (EMCS) will provide an equivalent spinning reserve load that can be used by owners when negotiating utility contracts with electricity suppliers in the deregulated environment of 2020.

Some of the most important issues in the lighting community today are related to the human dimension of occupant response to the indoor luminous environment. Lighting design has a direct impact on performance, health, and satisfaction in the built environment; however, the nature of that impact remains elusive. By 2020, the challenge is to conduct the research studies that will establish definitive causal linkages between design parameters and occupant impacts, and then apply these conclusions to the development of new technology and designs.

With only a modest RD&D effort, incrementally more efficient lighting components, including improved bulbs, fixtures, and controls, will be in use throughout all building types in 2020. Important improvements in lighting performance will result from using advanced techniques to improve the performance of fluorescent lamps and expanded use of diodes as light sources. Systems will be available to permit the integration of very-high efficiency lighting such as the sulfur lamp into common interior spaces.

A more vigorous program of lighting research could ensure that, by 2020, the nation will be discovering the virtues of lighting systems that deploy a mixture of centralized, energy-efficient, artificial light sources, tracking sunlight concentrators, and light distribution systems for buildings with high lighting usage. Offices and retail stores that require high lighting levels would be ideal candidates to field test such systems. A few, high-intensity, super-efficient light sources, centrally located, could then replace the numerous distributed light bulbs currently used. Whenever local climatic conditions permit, the sun could provide the light source in lieu of artificial sources. This piped lighting system could enhance many daylighting strategies based solely on architectural design elements. These piped systems, which use sunlight supplemented by super-efficient artificial light sources, could cut lighting-related power consumption in office buildings dramatically, since sunlight is usually available during normal office working hours. In addition to significant reduction in energy consumption for lighting, this system offers the potential to dramatically reduce lighting maintenance costs by using fewer artificial light sources and for much shorter periods.

Development of such lighting systems will require scientific breakthroughs and technical expertise in advanced artificial light sources, optical systems design, materials development, thin film coatings technology, fiber optics, photonics, manufacturing technology, systems engineering and modeling, instrumentation and controls, and human factors.

3.4.1.5 Controls, Communications, and Measurement

Computer technology has made possible a revolution in equipment and capabilities for electronic control of devices in homes, offices, and industry over the past 20 years. Similarly, significant advances in communications and information capability have introduced major changes in life styles and work practices over this same period. Over the next twenty years, this trend is expected to continue, offering additional opportunities to increase the efficient use of energy in buildings. The increasingly deregulated and converging energy and communications industries will play a major role in defining, commercializing, packaging, and delivering these new energy services and technologies to building owners. The fact that deregulation has resulted in greatly reduced RD&D investments by utilities underscores the need for a sustained, vigorous public-private partnership to ensure that energy-efficiency innovations emerge.

The communications industry has adopted programs for universal hardware and software connections between most functional components. The controls industry has initiated similar measures (*ASHRAE Journal*, November 1996, p.36). When universality is achieved, systems designers can begin to lay out and wire buildings with centrally located communications/control centers for all buildings including homes. This affords the opportunity to significantly reduce power requirements by eliminating full replication at each building station. That is, there needs to be only one video/audio receiver with low-power monitors at other sites, one computer central processing unit with low-power (e.g., liquid crystal) terminals where needed, one energy management control system (EMCS) with zone controllers where needed, and so on.

Developing and incorporating increased intelligence directed at energy use and control diagnostics in future generations of EMCS will allow these devices to maintain higher quality building environments with less expenditure of energy. Expected advances include EMCS with performance evaluation and equipment status tracking ability, as well as predictive capabilities. For example, EMCS with more powerful computational capability and with more sophisticated mathematical modeling can couple weather predictions with building response characteristics and occupancy, light, and moisture sensors to predict building performance and more closely match supply and demand of HVAC and lighting. Energy management and control systems may also be developed to enable the selection of least-cost energy service providers and rates (see further discussion under "Self-Powered Buildings" below).

Future EMCS will utilize networks like the Internet to transmit data, sound, and video for real-time remote analysis. This will permit integrated buildings service providers to track the performance of heating and cooling plants, diagnose failures, test machinery, and to communicate findings to building owners and operators, all without setting foot in the building. Some "full service" providers would also offer other services including energy management, security, and property and facilities management.

For appliances such as clothes washers and dryers, control and communications capabilities will allow for remote programming and cycle control as needed. Delayed start, checking on cycle progress from a remote location, and modification of settings remotely are all examples of potential capabilities. Additional research to develop more sophisticated sensors and control logic will increase future ability to measure and control energy use in the ever-widening pool of appliances and equipment used in buildings. Advanced sensors can check the status of food being cooked, room lighting levels, and thermal comfort and instruct controllers to automatically adjust appliances for optimum operation.

The development of advanced sensors, controls, and communications equipment needs to reflect the nature of changing "plug load" devices in buildings. The forecasted rapid growth in miscellaneous electricity consumption in buildings suggests an important future role for a broad range of novel control strategies to promote energy efficiency. In addition, advances in office equipment performance could mitigate potential increases in these miscellaneous electricity uses in many parts of the commercial sector (Komor 1996).

3.4.1.6 Self-Powered Buildings

The move toward a competitive marketplace for energy services such as gas and electricity will be essentially complete by 2010. By 2020, that market will have matured to accommodate complex buy-sell utility service arrangements monitored and administered by automated systems. This, combined with the advent of power production and improved energy storage technologies, will give building owners new levels of flexibility in meeting their energy requirements, as well as the possibility of revenue streams from the sale of energy or ancillary services. Buildings will cease to be simply

consumers of electric utility services but may supply all or a portion of their own energy requirements or, if the economics are right, sell to others. Removal of utility and environmental regulatory barriers would also accelerate the adoption of combined heat and power systems.

Small turbines running on natural gas are likely to be the first step in this process. These will allow buildings to generate their own electricity, with the reject heat from the turbines being used for domestic hot water or building space conditioning. Six manufacturers have announced actual or planned availability of gas turbine electric generators in the 50 kW range. Costs are uncertain, but will likely mature in the $750-$1000/kW range, including heat recovery equipment. Barriers to implementation include mechanical maintenance requirements as well as cost. The advent of automated control and diagnostic systems will make these distributed power plants as "forgettable" as any other piece of space conditioning equipment.

The next step in the development of the self-powered building will be the advent of low-cost fuel cells. The fuel cell is a unique technology that can revolutionize the way building power, heating, cooling, and water heating are generated and maintained.

Potential Additional Savings From Advanced Fuel Cell Technologies

In the high-efficiency/low-carbon scenario, fuel cell technology is also likely to make a contribution to reducing carbon emissions by 2010. While we have not included fuel cells in our main building sector scenarios, we examined recent technology projections from Arthur D. Little (ADL) and estimated the potential carbon savings from fuel cells in our high-efficiency/low-carbon case.

There are several different fuel cell technologies under development, including the phosphoric acid fuel cell (PAFC), the proton exchange membrane fuel cell (PEMFC), the molton carbonate fuel cell (MCFC), and the solid oxide fuel cell (SOFC). In addition, there are advanced gas turbines under development that could supply the same services as fuel cells, for comparable costs. We do not address the exact mix of technologies that might deliver carbon savings by 2010, but calculate the potential impacts assuming that some combination of these technologies would contribute savings.

Arthur D. Little created what they termed an "optimistic" scenario that resulted in 8200 MW of installed fuel cell capacity in commercial buildings by 2010. This estimate assumes a $50/tonne carbon charge and an aggressive commitment to building sector fuel cell development at or above current levels of funding. Their results imply that about 5% of all commercial building floor area in 2010 will have heat and power supplied by fuel cells.

Such penetration of a new and untried technology is ambitious by any measure. Because we are interested in a "best estimate", not an optimistic scenario, we chose to reduce the expected penetration to 65% of ADL's forecasted levels for our high-efficiency/low-carbon case (4.9 GW). For our more cautious case, we reduced the penetration again to 35% of ADL's forecasted levels (2.45 GW). As described in Table C-2.9 in Appendix C-2, implementation of this technology (or some combination of fuel cells and small advanced gas turbines in buildings) at the efficiency case level would result in primary energy savings beyond the high-efficiency/low-carbon scenario of about 0.14 quads, and additional carbon savings of about 2.5 MtC. The savings in the cautious case would be about half of the efficiency case savings. (See also Appendix D-3, in which the technical potential for commercial-sector advanced turbine systems in the 5-15 MW size range is estimated to be about 12 GW in 2010 at an estimated cost of $350/kW.)

To date, no other system identified provides all the benefits of the fuel cell. The fuel cell can generate electricity, provide heat and hot water, offer fuel flexibility, and operate quietly; in

addition, the fuel cell is modular, is a non-polluter, and has an overall conversion efficiency potential of 80% or better (Fiskum, 1997). Unlike gas turbines, fuel cells have no moving parts and are therefore inherently quiet. The ability to tailor the installation to the thermal needs of the building by selection of fuel cell technology will also be attractive. For example, proton exchange membrane (PEM) fuel cells, whose operating temperature does not exceed 100 degrees Centigrade, will be used in installations with only low-level waste-heat applications such as domestic water heating. Other types, such as molten carbonate and solid oxide fuel cells, operate at higher temperatures for applications requiring a higher quality heat resource.

Fuel cell prices currently range from $3000/kW to $5000/kW for commercially available phosphoric acid and near-term PEM cells, respectively. An aggressive RD&D program could cut these costs in half in less than ten years. Research needs include work on high-risk components and processes, including heat exchanger development to bring the high-temperature hydrogen stream in line with PEM cell stack temperature, and catalyst development to increase CO tolerance and to mitigate carbon monoxide contamination degradation of the catalyst (Fiskum, 1997).

Another key component of the self-powered building will be building-integrated photovoltaic (PV) panels, an application which will become more widespread as the costs of PV cells decline. Full implementation of this concept will require storage to achieve full flexibility, and such systems could include compact, high-efficiency flywheels as a means of taking advantage of the diversity between load and resource peaks. In some applications, notably commercial buildings located in high solar resource areas, the coincidence between the mid-afternoon resource peak and the demand for such services as air conditioning may minimize the need for storage. In any case, the availability of an electric power spot market, accessed by the building's automated energy management computer, will allow real time purchases of power when needed or sales of excess power when available. PV system costs are still in the range of $7000/kW without storage, but improvements in solar cell manufacturing processes and inverter technologies support program goals calling for reductions of more than 50% in ten years or less.

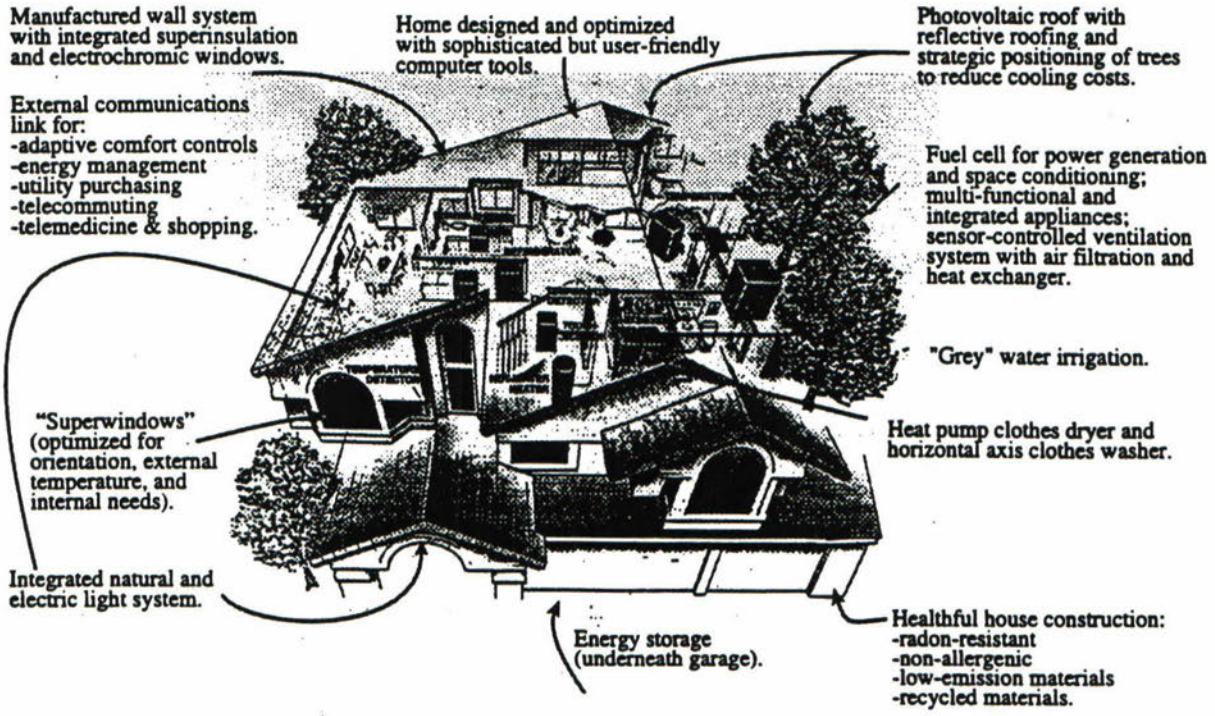
3.4.2 Best Practice Buildings in the Year 2020

3.4.2.1 "Best Practice" Housing in 2020

By the year 2020, a vigorous RD&D program could produce many advanced technologies that together will greatly reduce the average annual energy budgets of American families. The "Best Practice" home of the year 2020 is defined as a home that employs those energy technologies that are predicted to have the lowest life-cycle costs when purchased in the year 2020, under the assumption that a "high-efficiency/low-carbon" scenario unfolds between now and then. A collage of these best practice features is shown in Figure 3.7.

The best practice home in the year 2020 will be factory built and shipped to its site as modules or subassemblies. The use of integrated systems design and CAD/CAM technologies for "mass customization" will have produced these components and modules to reflect the particular requirements of the home buyer. On-site construction work will consist primarily of assembling these manufactured components and modules, rather than fabrication from raw materials.

Figure 3.7 "Best Practice" Home of the Year 2020



The best practice home will use affordable, modular, and therefore flexible techniques to permit longer occupancy. Durability and quality of the basic structure will significantly improve over the year 1997, and adaptive envelopes will provide significant energy advantages. Material consumption in residential structures will be reduced through the use of recycled materials and engineering advances in materials, systems, and assemblies which provide stronger, more durable, lighter, and less expensive structures. HVAC systems will be right-sized and refined to match reduced cooling and heating loads and improved comfort features of the envelope. Thermal distribution systems will effectively transport heating and cooling to the conditioned space. Climate-appropriate advanced ventilation strategies will range from passive ventilation systems to filtered systems to heat exchange systems.

Thermal mass will be strategically used to improve comfort and efficiency. "Smart" windows will see widespread use in upscale houses and for specific rooms and orientations in general housing. When properly linked via controls and sensors to HVAC systems, improved comfort can be provided with downsized systems.

Widespread use of paneling and shingles with built-in PV arrays, fuel cells, and advanced energy storage systems will significantly reduce overall building sector non-renewable energy needs and will either deliver electricity back to the grid or will provide energy for family electric vehicles. Building-integrated photovoltaics will be widely employed in new home construction, and a strong retrofit market for PV shingles will have developed as well.

Advanced high-efficiency lighting systems actively operating with an array of daylighting and site/task strategies will optimize building luminosity and reduce energy consumption. Appliances, lighting, and building control systems will all incorporate smart technology to closely match energy and water supply and ambient conditions with need. The best practice home in 2020 will be low in volatile organic pollutants due to the use of low-emitting building materials, and will be equipped with sensor-controlled energy-efficient ventilation and air cleaning to provide good air quality. Automatic load modulation of heating and cooling systems in response to varying weather, environment, and occupant demands will be installed in best practice residences. In addition to improved sensors and controls, zoning and variable loading of the heating and cooling system will be used.

The home may have a new generation of high-efficiency gas appliances operating much closer to combustion temperatures, or it may be equipped with an integrated water heating/space conditioning electric heat pump system that minimizes waste heat. These multi-functional systems will focus on occupant thermal comfort rather than conditioning the space.

Distributed water heating capability (i.e., instant heating at the faucet) may provide supplemental "on-demand" water heating. Water use and energy efficiency will also be enhanced by improved design and technology for distribution systems. In addition, a greywater irrigation system equipped for sterilization of effluent may reduce the water required for landscaping, gardens, and lawns in arid or water-constrained regions of the country.

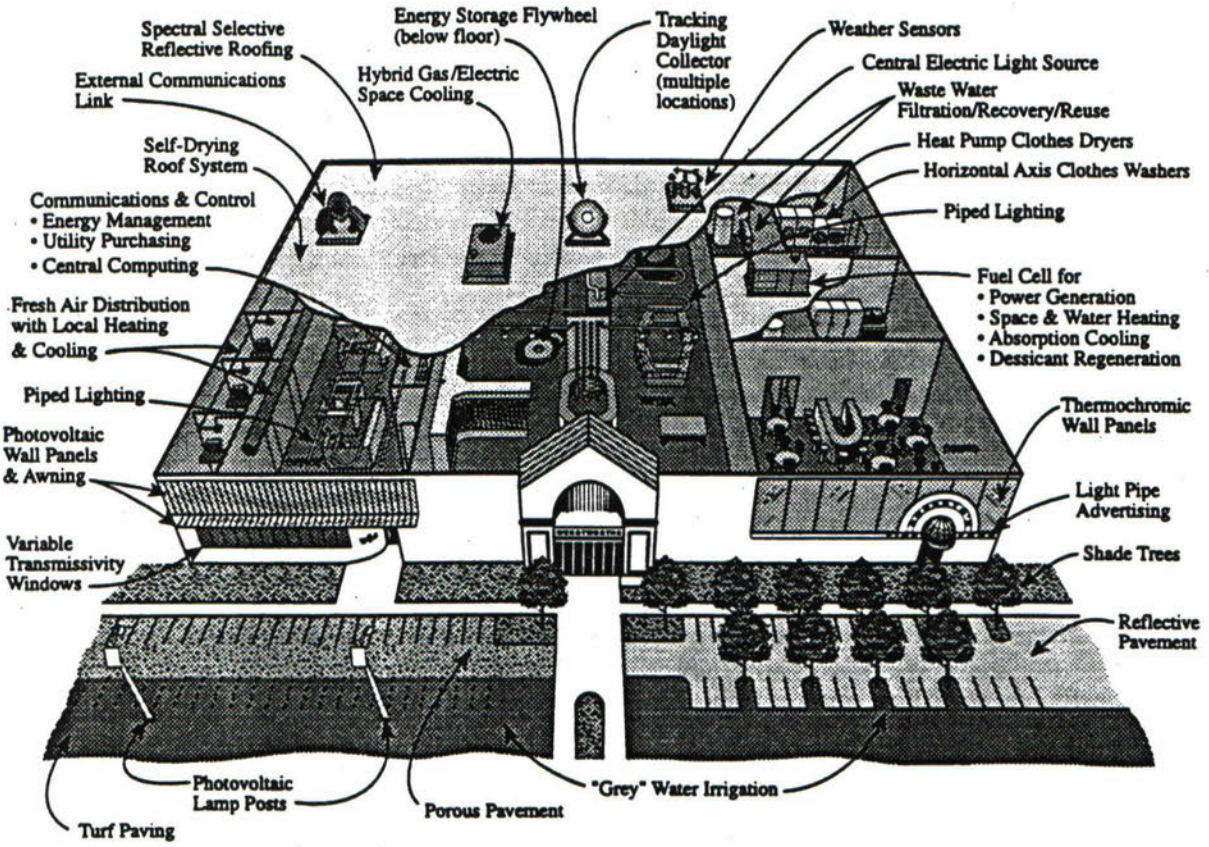
Home computers and sophisticated communication systems will begin to permit the use of the home as the location of office, secondary school, routine medical treatment, and selected shopping activities. This will begin to change the "mix" of building types as well as the need to commute to these activities.

3.4.2.2 "Best Practice" Commercial Buildings in 2020

By the year 2020, "best practice" commercial buildings will have many advanced technologies that will greatly reduce the cost of their utility requirements. More advanced programming, design, construction and commissioning processes will enable both reduced first costs and reduced operating costs. Varying designs will match building systems with the wide range of climate conditions found in the U.S. Commercial buildings will be designed and constructed to provide indoor environments that increase the productivity of workers. A collection of alternative technologies and options that could be cost-effective in the year 2020 – under the high-efficiency/low-carbon scenario – are illustrated in Figure 3.8. The drawing shows a composite commercial building containing retail, office, laundry, and dining facilities.

Commercial buildings will continue to look similar to those existing today. The primary change will be in the "mix" of these facilities as the advances in electronic information dissemination reduce the need for physical interaction, and therefore the size, of some commercial buildings. Some "traditional" commercial buildings, involved primarily in the transfer of information and knowledge (e.g., offices and libraries) will be significantly down-sized as their physical interaction (people-related) activities are replaced with electronic communication capabilities. Improved communications (combined with just-in-time inventory control) will also permit the reduction or elimination of many stock rooms as well as warehousing and distribution facilities. Many commodities will flow directly from production to end-use.

Figure 3.8 "Best Practice" Composite Commercial Building of the Year 2020



The state-of-the-practice commercial buildings will rely heavily on manufactured components for their construction. One-of-a-kind structures may continue to have many site-built components, but construction of commercial buildings of standard design (e.g., franchise restaurants and retail stores), will primarily involve assembly of manufactured components or installation of complete modules. To make school buildings more affordable to build and operate, such modular construction of schools may also become commonplace. Quality and material improvements, that cannot be afforded on a one-of-a-kind basis, will be assimilated into the high-volume manufacturing process.

Low-emissions construction materials and furnishings will be used in the building to reduce the energy used for ventilation as well as adverse health effects in occupants. Ventilation air will be filtered to remove infectious agents and allergens that cause illness in workers and lost productivity, and the use of recirculated air will be minimized. Individual controls will enable workers to adjust lighting to the most comfortable intensity for their work and for reduced glare. Daylighting will be more widely used to enhance worker satisfaction and comfort. "Best practice" commercial buildings will deal effectively with issues of moisture, thermal bridges, thermal distribution, air infiltration, and air quality.

By the year 2020, "best practice" buildings will also be delivering major performance improvements through the use of an integrated systems-oriented and optimizing design process. The energy performance improvements from an increased emphasis on design and commissioning will be accompanied by improved building energy services and lower overall first costs.

Improved information about building performance will allow informed design. Right-sizing and modular staged-operation designs with flexible uses and good part-load operating characteristics will reduce peak electrical demands as well as overall energy use. Information management systems for tracking equipment performance and status will ensure persistence of savings from energy-efficiency measures throughout the building life-cycle.

Larger commercial buildings will have many space conditioning equipment choices, including hybrid gas/electric space cooling systems and fuel cells for power generation, space and water heating, absorption cooling, and desiccant regeneration. Chlorofluorocarbon refrigerants will be completely removed from the buildings sector by 2020 and hydrogenated chlorofluorocarbons will be found only in older equipment.

The "best practice" commercial building will have highly-efficient centralized electric light sources combined with tracking daylight collectors connected to "piped" light distribution systems. In addition, natural lighting through windows and skylights will illuminate interior spaces during daytime hours.

Most new and existing buildings will use smart control technologies to optimize the building load configuration in response to weather, occupant demands, and utility rate structures. Natural conditions and building supply systems will be automatically balanced to adjust for predicted weather and occupant use. In order to permit greater use of the external environment to improve internal comfort conditions and reduce energy use, load control will also regulate the variable R-value wall panels and variable transmittance fenestration. Photovoltaic roofing shingles, wall panels, and awnings will contribute to the power requirements of state-of-the-practice commercial buildings.

The widespread use of "cool community" principles will mitigate the impact of urban heat island effects on major new developments and communities. In addition to reflective roofing and pavement, this may include using porous pavement, interspersing grass with concrete in lightly used parking areas, and installing grey water irrigation systems.

3.5 IMPROVEMENTS TO THIS ANALYSIS

There are a few areas where additional work could improve the accuracy of the calculations described in sections 3.2 and 3.3 above.

- Ducts in residential buildings typically leak 15-30% of the air passing through them. In addition, many of these ducts are inadequately insulated. The end result is that significant amounts of heating and cooling energy are wasted, particularly when ducts are in unconditioned spaces. A few relatively inexpensive measures (particularly the aerosol duct sealing technology) can reduce duct air and heat leakage significantly, even in existing buildings (Modera et al. 1996). Such measures are not included in the savings estimates for space conditioning equipment discussed above, and it is likely that an additional 0.5 to 1 quad of primary energy savings could be achieved by 2010 by widespread implementation in the residential sector.

- The savings estimates for commercial water heating and cooking, as well as for miscellaneous natural gas use, could be refined significantly. The data available on these end-uses are sparse.

- No savings have been estimated for commercial office equipment, but opportunities may arise to use voluntary programs (such as the highly successful ENERGY STAR office equipment program) to promote efficiency as this end-use evolves over the next decade.

- No savings have been included for commercial building shell measures. Windows strongly influence heating, cooling, and lighting loads in all commercial buildings, and insulation can be important for smaller commercial buildings.

- No savings have been included for ground source heat pumps in residential and small commercial buildings.

- No savings have been included for the advanced heat exchanger technology currently being commercialized by Modine, which reduces air conditioner and heat pump energy use by 15-20% and *reduces* the cost of the heat exchanger.

- No savings have been included for integrated systems that combine heating and water heating, or heating, cooling, and water heating.

- No savings have been included for district heating and cooling systems with combined heat and power.

- More data are needed on the effects of large-scale tree planting on energy use, and this policy option needs to be incorporated into the estimates of potential 2010 impacts.

- No credits have been calculated for downsizing of HVAC equipment associated with more efficient building shells.

- No attempt has been made to correct for changes in internal gains associated with energy savings for appliances located within conditioned spaces. Recent work in U.S. commercial buildings indicates that the heating penalties roughly offset the cooling benefits in both primary energy and dollar terms (when averaged across the entire commercial sector). There is no comparable analysis for average residences in the U.S., but an analysis for Europe (Krause et al. 1995) finds that this effect leads to small net energy penalties in residences.

- Because energy savings from miscellaneous electricity use are so important to the results of the buildings sector, it is crucial that more research be carried out, both to characterize how energy is used in the miscellaneous category and to identify technologies for improving the efficiency of sub-categories within the miscellaneous category of electricity use.

On balance, we believe that adding these items to the analysis would increase savings and decrease costs.

3.6 SUMMARY AND CONCLUSIONS

Our analysis leads to the following key results for 2010:

- The "efficiency" scenario results in 1.9 quads (5.3%) less energy use and 25 MtC (4.4%) fewer carbon emissions than the "business-as-usual" scenario in 2010. This represents a savings of $18 billion in fuel costs in 2010, which is purchased with an annualized incremental cost of $7 billion in efficiency improvements.

- The "high-efficiency/low-carbon" scenario results in 4.3 quads (12%) less energy use and 60 MtC (11%) fewer carbon emissions than the "business-as-usual" scenario in 2010. This represents a savings of $33 billion in fuel costs in 2010 resulting from an annualized incremental expenditure of $13 billion on efficiency improvements.

- In the residential sector, the greatest energy and carbon savings are achieved in miscellaneous electricity, lighting, space conditioning, and water heating. In the commercial sector, the greatest energy and carbon savings are achieved in miscellaneous electricity, space conditioning, and lighting.

- For both residential and commercial buildings, about 90% of the primary energy saved is electricity in both the "efficiency" and the "high-efficiency/low-carbon" scenarios.

- The time frame of the study (13 years) limits the penetration of efficiency technologies, because we only consider efficiency upgrades at the time of equipment retirement (no early retirements). About one-fifth of buildings sector primary energy consumption is not affected in our efficiency scenarios because the lifetimes of certain types of equipment are comparable to or longer than the analysis period (see Table C-2.11 in Appendix C-2). Savings from this "untouched energy" would eventually be achieved in our efficiency and high-efficiency cases, but only after 2010.

Six R&D areas offer great promise to reduce significantly the energy requirements in U.S. buildings in 2020:

- Advanced construction methods and materials will provide increased efficiency and improved building energy services, often with lower overall first costs. Construction methods in this time frame will consist primarily of factory-manufactured modules and components assembled on-site, enabling systems engineering to deliver greater energy efficiency, more affordable construction, and increased use of recycled materials. Building information management systems will improve life-cycle performance including feedback for continuous improvement in design.

- Environmental integration will produce buildings matched to the wide range of climatic conditions, and adaptive envelopes will capitalize on changing outdoor conditions to reduce energy use and improve occupant comfort and productivity. In addition, environmental integration strategies such as reflective roofing materials and turf paving will reduce urban heat island effects.

- Multi-functional equipment and integrated systems design offer the opportunity for a quantum leap in efficiency improvements. For example, combining the functions of several appliances into a single, highly effective device that puts to use waste heat and employs high-efficiency components to perform dual functions. Also, the use of integrated systems-oriented design and commissioning processes will provide efficiency improvements along with improved energy services and reduced first costs.

- Advanced lighting systems in 2020 will include a range of improved technologies such as improved controls; more high-efficiency small sources matched to improved luminaires; daylighting systems; and centralized sources with advanced distribution systems. Appropriate combinations of such systems will have the potential to employ highly efficient artificial light sources in combination with tracking sunlight concentrators, light pipes, and daylighting to meet the occupants' precise functional needs for lighting with an order-of-magnitude reduction in energy use.

- Controls, communications, and measurement capabilities will enable greatly reduced energy requirements by matching current and predicted weather conditions, utility rates, and internal environmental measurements to meet fluctuating occupant requirements while expending less energy.

- Finally, self-powered buildings will have fuel cells or small turbines, PV building components, and energy storage devices to provide building owners with new levels of flexibility in meeting their energy needs and generating revenues from electricity sales.

Achieving this promise will require significant R&D expenditures over the next twenty years, but will yield benefits that more than offset these expenditures.

3.7 REFERENCES

American Home Appliance Manufacturers. *AHAM Fact Book, 1996*, Chicago, IL.

Andrews, Steve. 1994. "Perry Bigelow: Energy Efficiency Maestro". *Home Energy*. March/April. p. 13.

Brown, R. E. 1994. *Estimates of the Achievable Potential for Electricity Efficiency Improvements in U.S. Residences*. In Proceedings of the 1994 ACEEE Summer Study on Energy Efficiency in Buildings. Washington, DC: American Council for an Energy-Efficient Economy. Vol. 7, page 55.

Brown, R. E. 1993. *Estimates of the Achievable Potential for Electricity Efficiency in U.S. Residences*. M.S. Thesis, Energy and Resources Group, University of California, Berkeley.

Christian, J. E. 1991. "Thermal Mass Credits Relating to Building Envelope Energy Standards," *ASHRAE Transactions*, Vol. 91.

Darrow, C. 1994. "A House of the Future," *The International Panel and Engineered-Wood Technology Exposition Conference Proceedings*, Atlanta, Georgia, October 5-7.

Energy Information Administration (EIA). 1996. *Annual Energy Outlook 1997, with Projections to 2015*. Washington, DC : U.S. Department of Energy, DOE/EIA-0383(97), December.

Energy Information Administration (EIA). 1995. *Emissions of Greenhouse Gases in the United States, 1987-1994*. Washington, DC: DOE Energy Information Administration, DOE/EIA-0573(87-94).

Fine, H. A. and D. L. McElroy. 1989. "Assessment of the Energy Conserving Potential of Active (Variable Thermal Resistance and Switchable Emittance) Building Thermal Envelope Systems," *Thermal Performance of the Exterior Envelopes of Buildings IV, Dec. 4-7, 1989*. ASHRAE.

Hanford, J.W., J.G. Koomey, L.E. Stewart, M.E. Lecar, R.E. Brown, F.X. Johnson, R.J. Hwang, and L.K. Price. 1994. *Baseline Data for the Residential Sector and Development of a Residential Forecasting Database*. Berkeley, CA: Lawrence Berkeley National Laboratory, LBNL-33717.

Houghton, David J., Robert C. Bishop, Amory B. Lovins, Bristol L. Stickney, James J. Newcomb, Michael Shepard, and Bradley J. Davids. 1992. *The State of the Art: Space Cooling and Air Handling*. Competitek. August.

Kammerud, R. C. 1995. *Energy Use Impacts of Advanced Envelope Materials: Assessment of Mechanisms for Altering Radiation Absorptivity*. Oak Ridge, Tennessee: Oak Ridge National Laboratory, ORNL/Sub/86X-SP110V.

Komor, P. 1996. Cooling Demands from Office Equipment and Other Plug Loads. E-Source Tech Update TU-96-9. July 1996. Boulder CO. ESource.

Konopacki, Steven, Hashem Akbari, Mel Pomerantz, S. Gabersek, and Lisa Gartland. 1997. *Cooling Energy Savings Potential of Light-Colored Roofs for Residential and Commercial Buildings in 11 U.S. Metropolitan Areas*. Ernest Orlando Lawrence Berkeley National Laboratory. LBNL-39433. May.

Koomey, J.G., C. Atkinson, A. Meier, J.E. McMahon, S. Boghosian, B. Atkinson, I. Turiel, M.D. Levine, B. Nordman, and P. Chan. 1991. *The Potential for Electricity Efficiency Improvements in the U.S. Residential Sector*. Berkeley, CA: Lawrence Berkeley National Laboratory, LBNL-30477.

Koomey, J. G., C. Dunham, and J. Lutz. 1994. *The Effect of Efficiency Standards on Water Use and Water Heating Energy Use in the U.S.: A Detailed End-Use Treatment*. Berkeley, CA: Lawrence Berkeley National Laboratory, LBNL-35475.

Koomey, J.G., F.X. Johnson, J. Schuman, E. Franconi, S. Greenberg, J.D. Lutz, B.T. Griffith, D. Arasteh, C. Atkinson, K. Heinemeier, Y.J. Huang, L. Price, G. Rosenquist, F.M. Rubinstein, S. Selkowitz, H. Taha, and I. Turiel. 1994. *Buildings Sector Demand-Side Efficiency Technology Summaries*. Berkeley, CA: Lawrence Berkeley National Laboratory, LBNL-33887.

Koomey, J. G., D. A. Vorsatz, R. E. Brown, and C. S. Atkinson. 1997. *Updated Potential for Electricity Efficiency Improvements in the U.S. Residential Sector*. Berkeley, CA: Lawrence Berkeley Laboratory, LBNL-38894 (DRAFT).

Koomey, J. G., and M. C. Sanchez. 1997. Trends in Carbon Emissions for Buildings. Submitted to Energy Policy in May, 1997.

Koomey, J. G., M. C. Sanchez, D. A. Vorsatz, R. E. Brown, and C. S. Atkinson. 1997. *The Potential for Natural Gas Efficiency Improvements in the U.S. Residential Sector*. Berkeley, CA: Lawrence Berkeley Laboratory, LBNL-38893 (DRAFT).

Krause, Florentin, Eric Haites, Richard Howarth, and Jonathan Koomey. 1993. *Energy Policy in the Greenhouse. Volume II, Part 1. Cutting Carbon Emissions–Burden or Benefit?: The Economics of Energy-Tax and Non-Price Policies*. El Cerrito, CA: International Project for Sustainable Energy Paths.

Krause, Florentin, David Olivier, and Jonathan Koomey. 1995. *Energy Policy in the Greenhouse. Volume II, Part 3B. Negawatt Power: The Cost and Potential of Low-Carbon Resource Options in Western Europe*. El Cerrito, CA: International Project for Sustainable Energy Paths.

Lawrence Berkeley National Laboratory. 1996. *Draft Report on Potential Impact of Alternative Efficiency Levels for Residential Cooking Products*. Berkeley, CA: Lawrence Berkeley National Laboratory.

Lawson, C. 1996. The Price of Commissioning Equals Cost Savings. ASHRAE Journal 38:1:30-34. Atlanta GA. ASHRAE.

Lovins, A. 1992. Energy-Efficient Buildings: Institutional Barriers and Opportunities. E-Source Strategic Issues Paper. SIP1. December 1992. Boulder CO. ESource.

Mills, Evan, and Arthur H. Rosenfeld. 1994. "Non-Energy Benefits as a Motivation for Making Energy-Efficiency Improvements". Presented at the American Council for an Energy-Efficient Economy (ACEEE) 1994 Summer Study on Energy Efficiency in Buildings in Asilomar, CA.

Modera, M.P., D.J. Dickerhoff, O. Nilssen, H. Duquette, and J. Geyselaers. 1996. "Residential Field Testing of an Aerosol-Based Technology for Sealing Ductwork". Presented at the ACEEE 1996 Summer Study on Energy Efficiency in Buildings in Asilomar, CA. Published by American Council for an Energy Efficiency Economy (also LBNL-38554).

Rosenfeld, Arthur H., Joseph J. Romm, Hashem Akbari, Melvin Pomerantz, and Haider Taha. 1996. "Policies to Reduce Heat Islands: Magnitudes of Benefits and Incentives to Achieve Them". Presented at the ACEEE 1996 Summer Study on Energy Efficiency in Buildings in Asilomar, CA. Published by American Council for an Energy Efficiency Economy.

Rosenfeld, A. H., J. J. Romm, H. Akbari, and A. C. Lloyd. 1997. "Painting the Town," *Technology Review*, February.

Sanchez, Marla. 1997. Miscellaneous Electricity Use in U.S. Residences. Master's Thesis (MS). University of California, Berkeley, Energy and Resources Group.

Schwolsky, Rick. 1997. "Positive Tradeoffs". *Builder Magazine*. January. p. 332.

Sezgen, A. O., E. M. Franconi, J. G. Koomey, S. E. Greenberg, and A. Afzal. 1995. *Technology Data Characterizing Space Conditioning in Commercial Buildings: Application to End-Use Forecasting with COMMEND 4.0*. Berkeley, CA: Lawrence Berkeley Laboratory, LBL-37065.

Sezgen, A. O. and J. G. Koomey. 1995. *Technology Data Characterizing Refrigeration in Commercial Buildings: Application to End-Use Forecasting with COMMEND 4.0*. Berkeley, CA: Lawrence Berkeley Laboratory, LBL-37397.

Shepard, et al. 1995. Commercial Space Cooling and Air Handling Technology Atlas. June 1995. Boulder CO. ESource.

Smith, J. A. and J. D. Rivera. 1989. "Beyond the Year 2000: A Broad Analysis of the Future Trends that will Affect Buildings," *Buildings of the 21st Century: Developing Innovative Research Agendas*, Gersau, Switzerland, May 16-18.

Todesco, G. 1996. Super-Efficient Buildings: How Low Can You Go? ASHRAE Journal. 38:12:35-40. Atlanta GA. ASHRAE.

U.S. Department of Commerce. 1996. *Statistical Abstract of the US*. Washington, DC: Economics and Statistics Administration, Bureau of the Census.

U.S. Department of Energy (DOE). 1990. *Technical Support Document: Energy Conservation Standards for Consumer Products: Dishwashers, Clothes Washers, and Clothes Dryers*. Washington, DC: DOE, DOE/CE-0299P.

U.S. Department of Energy (DOE). 1993. *Technical Support Document: Energy Efficiency Standards for Consumer Products: Room Air Conditioners, Water Heaters, Direct Heating Equipment, Mobil Home Furnaces, Kitchen Ranges and Ovens, Pool Heaters, Fluorescent Lamp Ballasts, and Television Sets*. Washington, DC.: DOE, DOE/EE-0009.

U.S. Department of Energy (DOE). 1995. *Technical Support Document: Energy Efficiency Standards for Consumer Products: Refrigerators, Refrigerator-Freezers, & Freezers*. Washington, DC: DOE.

Vorsatz, D. A. and J. G. Koomey. 1997. *The Potential for Efficiency Improvements in the U.S. Commercial Lighting Sector*. Berkeley, CA: Lawrence Berkeley Laboratory, LBNL-38895 (DRAFT).

Webber, C. 1997. Personal Communication regarding LBNL Technical Analysis of Reduction of Standby Electricity Use in Televisions and Video Cassette Recorders. Berkeley, CA: Lawrence Berkeley National Laboratory.

Wendt, R. L.. 1994. "Housing 2020: The Future of Wood in U.S. Dwellings," *The International Panel and Engineered-Wood Technology Exposition Conference Proceedings*, Atlanta, Georgia, October 5-7.

Westphalen, D., R. A. Zogg, A. F. Varone, and M. A. Foran. 1996. *Energy Savings Potential for Commercial Refrigeration Equipment*. Prepared by Arthur D. Little, Inc. for the Building Equipment Division, Office of Building Technologies, US Department of Energy. ADL Reference No. 46230.

ENDNOTES

[1] A "cost-effective technology" in our analysis is generally defined as a technology that is the minimum life-cycle cost option using a 7% real discount rate and the lifetime of the option. Life-cycle cost is the discounted sum of incremental capital costs and operating costs over the life of the option. This criterion is the equivalent of the cost of conserved energy equaling the value of displaced or saved energy.

[2] To determine which measures are less expensive than the average price of purchased fuel or electricity and hence cost-effective, we calculate cost of conserved energy (CCE) using the following equation:

$$\text{CCE (¢/kWh)} = \frac{\text{Capital Cost \%} \cdot \frac{d}{(1-(1+d)^{-n})}}{\text{Annual Energy Savings}}$$

where d is the discount rate and n is the lifetime of the conservation measure. The numerator in the right hand side of the equation is the annualized cost of the conservation investment. Dividing annualized cost by annual energy savings yields the CCE.

[3] Carbon emissions are derived from the product of end-use energy (by fuel) and carbon emissions factors of MtC/quad of primary energy taken from EIA (1996). The total cost of energy services is the estimated amount spent on energy consumption plus the incremental efficiency cost for purchasing and operating high-efficiency technologies. In the business-as-usual scenario, the incremental efficiency cost is defined to be zero.

[4] Miscellaneous energy use involves end-uses in buildings that are not currently allocated to other end-uses, namely refrigeration and freezing, space conditioning, lighting, cooking, drying, and water heating. In order to more accurately estimate energy savings potential, we divided the miscellaneous end-use into three electricity categories and two fuel categories. The three electricity categories were: electronics (e.g., color televisions and video cassette recorders), motors (e.g., fans and pumps), and heating (e.g., waterbed heaters, coffee makers, etc.). About 20% of miscellaneous electricity is associated with standby losses of equipment that are turned off but still draw a small amount of power (the so-called "leaking" component of miscellaneous). See Sanchez (1997) for more details.

[5] The scale for 2010 carbon emissions for electricity end-uses in Figures 3.2 and 3.3 is slightly different than shown for 1997, since a 2.5% decline in the carbon intensity of electricity generation is projected for 2010, but this does not significantly change the results shown in the figures. For example, residential miscellaneous electricity carbon emissions in 2010 are 92 MtC but appear slightly greater (~94 MtC) in Figure 3.2.

[6] Major contributions to this section were made by George Courville, Mike MacDonald, Jeff Muhs, John Tomlinson, Jim VanCoevering, and Bob Wendt (Oak Ridge National Laboratory).

[7] With thermal switching, the absorptivity and emissivity change between a high and a low value at a set material temperature; with short wavelength switching, the solar absorptivity changes at a specific wavelength radiation flux; and with long wavelength switching, the emissivity changes when the temperature of the radiative environment satisfies certain conditions.

[8] Heat pump water heaters are an exception to this general pattern. They have been demonstrated in the field to deliver up to three times as much energy in hot water as is provided to the unit in electricity; however, the technology's relatively high cost is a major market barrier. Technology breakthroughs could result in significant reductions in first costs, enabling greater market penetration of heat pump water heaters.

Chapter 4

THE INDUSTRIAL SECTOR

4.1 INTRODUCTION

This chapter presents an assessment of the possible contribution that an invigorated effort to move energy-efficient technologies that are commercially available, or near commercialization, into the market could make to reducing greenhouse gas emissions from the US. industrial sector by 2010. We begin with some background information on our approach to the assessment and how that approach is shaped by the complexities of the U.S. industrial sector and the available analytical tools for this sector. We then describe the results of our model-based scenario analysis for the year 2010. In subsequent sections we provide examples of the types of technologies that need to come into widespread use to achieve the scenario results. Widespread adoption of these technologies requires appropriate policies (e.g., accelerated research and development (R&D), fiscal incentives, and market conditions). Finally, we describe qualitatively, and illustrate with examples, the role of R&D in providing a steady stream of advanced technologies that can continue to reduce industrial energy intensity and greenhouse gas emissions, into the foreseeable future. Details of the models used in the analysis and the technologies described in this chapter are provided in appendices.

4.1.1 Approach

The industrial sector is extraordinarily complex and heterogeneous. By definition, it includes all manufacturing, as well as agriculture, mining, and construction activities. The manufacturing industries range from those that transform raw materials into more refined forms (e.g., the primary metals and petroleum refining industries) to those that produce highly finished products (e.g., the food processing, pharmaceuticals, and electronics industries). Hundreds of different processes are used to produce thousands of different products. The U.S. chemical industry alone produces more than 70,000 different products at over 12,000 plants. Even within a manufacturing industry, individual firms vary greatly in the outputs they produce and how they produce them. Further, two plants producing identical outputs can use different processes, and two plants using identical processes can use different vintages and types of equipment. In some industries, plants employing the same basic processes can produce a different mix of outputs.

This complexity makes it difficult to conduct this assessment in a "bottom-up" fashion.[1] The available time and resources do not allow us to (1) catalog all of the advanced technologies whose use might be increased under an invigorated effort to move them into the market, (2) identify all the processes in which these technologies might be used, (3) estimate the fraction of the plants that are not already using these technologies, and (4) determine which of these plants would be likely to choose to invest in them under the invigorated effort noted above. Instead, we rely on publicly-available computer-based models to develop rough estimates of the potential for increased investment in energy efficiency more generally, and then supplement these estimates with examples of technologies, the adoption of which would achieve the model results under an invigorated effort to move them into the market.

4.1.1.1 Scenario Analysis

For the scenario portion of the analysis, the ideal analytical tool would be an industrial model that is publicly-available, complete and up-to-date, and has a stock-adjustment mechanism as well as detailed, technology-specific conservation supply curves for all important industrial processes that are affected by energy prices, capital recovery rates, and other economic parameters. We would also like

to be able to relate the modeling results to those reported in the US. Department of Energy's *Annual Energy Outlook 1997* (AEO97), which is prepared by the Energy Information Administration using the National Energy Modeling System (NEMS) (EIA 1997b).

No existing modeling tool has all of these features. Instead, we employ two modeling tools that, when used together, provide us with the features we need: (1) the Long-Term Industrial Energy Forecasting (LIEF) model, which provides a mechanism for evaluating general investment in conservation technology as a function of energy prices, capital recovery rates, and other parameters, and (2) the NEMS Industrial Module (NEMS-IM), which captures the effects on energy intensity of groups of specific technologies, but does not model investment in these technologies as functions of energy prices or any other factors. (See Appendix D-1 for a description of these two models and the industry disaggregation scheme used in each.)

We used these two models to develop three scenarios: a "business-as-usual" (BAU) case, an "efficiency" (EFF) case, and a "high-efficiency/low-carbon" (HE/LC) case. These cases are defined, and their results described, in Section 4.2. Our general approach was to use the AEO97 reference case (developed using the NEMS model) as our BAU case. Using the macroeconomic and energy price assumptions in the AEO97 reference case, we adjusted the LIEF model's base case slightly to more closely approximate the overall energy forecast in the AEO97.[2] We then ran the adjusted LIEF model to obtain an efficiency and high-efficiency/low-carbon case. We computed the difference between the LIEF BAU case and the LIEF efficiency case ("delta one"), and between the LIEF BAU case and the LIEF HE/LC case ("delta two"). We applied the LIEF model "deltas" to the NEMS (AEO97 base) results to compute our final estimates for potential greenhouse gas emissions reductions. We also used the NEMS model to explore the extent to which capital stock turnover and technology performance would have to increase to correspond to "delta one" and "delta two."

4.1.1.2 Technology Examples

The technology discussion focuses on energy-conserving technologies that, as a result of past R&D, are currently available for purchase in the market or are highly likely to enter the market within the next few years. While these technologies are available, they have not necessarily been widely adopted and, under current circumstances, may not be – thus the need for an accelerated effort to encourage their adoption and achieve the savings that the models suggest are possible. While there are many reasons for an invigorated effort to adopt these technologies, some of which we discuss later, we temper our expectations to be sensitive to the slow turnover of heavy equipment in industry.[3] Another timing issue is that some energy-intensive industries also have "windows of opportunity" during the next few decades where aging capital equipment must be replaced for environmental or competitive reasons.

We focus on seven energy-intensive industries that are either modeled in detail by the NEMS and LIEF models or are the focus of the DOE Office of Industrial Technologies' (OIT) Industries of the Future process, sometimes referred to as "Vision Industries": forest products,[4] glass, iron and steel, metal casting, aluminum, chemicals, and petroleum refining. These major energy-using sectors account for about 80% of manufacturing energy use (see Figure 4.1). We also look at cross-cutting technologies (such as energy-efficient motors) that affect all industries. These energy-intensive industries are briefly described in the box below.

Energy-Intensive Industries

Industries are characterized using data collected by the Bureau of the Census from establishments (plants) that are classified in a particular industry based on the value of the production of the plant and the industry that is identified as the origin of that product. This classification system, known as the Standard Industrial Classification (SIC), is being superceded this year by the North American Industry Classification System (NAICS). In addition to economic information collected by the Census, energy consumption is collected for the Energy Information Administration in the Manufacturing Energy Consumption Survey (MECS).

According to the 1994 MECS, the most energy-intensive industries were, in descending order, Petroleum and Coal Products (NAICS 324); Paper and Allied Products (321); Chemicals and Allied Products (325); Primary Metals (331); and Stone, Clay and Glass Products (327). The range of intensity of these industries is from 44.3 to 13.3 thousand Btu per dollar of output (TBtu/$). A brief description of these five most energy-intensive industries follows.

Petroleum and Coal Products. The major activity in this industry is converting crude petroleum into the petroleum products widely used in our economy – gasoline, diesel, fuel oil and lubricants. The process is a complex one of first separating the crude into different products, then recombining these components into the desired products. The separation is done through distillation and cracking that requires high temperatures and pressures, and is affected by the density of the original crude. Environmental considerations have greatly increased the complexity of this process, as reformulated and oxygenated fuels are increasingly needed to assure clean air quality. Another factor that has made for increased energy use in this industry is the declining availability of light crude and the greater processing requirements for heavy crude. Petroleum refining is the most energy-intensive industry with an intensity of 44.3 TBtu/$.

Paper and Allied Products. This industry converts fiber, usually from wood, into paper, pulp or paperboard, and then into a variety of products. The process begins with wood, which is first debarked and chipped, then either mechanically or chemically reduced to a slurry that is bleached, then formed into pulp, paper, or board. Though paper making is a very energy-intensive process, much of the energy used is derived from the biomass that is the basic feed stock for the process. The Forest Products Vision process combines this industry with wood products manufacturing, which includes saw mills, plywood mills and engineered wood products. In 1994, energy intensity was 18.5 TBtu/$.

Chemical and Allied Products. The major segments of this industry are basic chemicals; resins, synthetic rubber and manmade fibers; pesticides, fertilizer and other agricultural chemicals; pharmaceuticals and medicines; paints, coatings, sealants and adhesives; soap, cleaning compounds and toilet preparations; and other chemical products. Basic chemical production includes petrochemicals, industrial gases, and other inorganic chemicals, and other organic chemical manufacture. Basic chemical production uses the bulk of the energy required by this industry and creates the largest volume of products. In all of chemical manufacturing, heat and pressure are used to separate and combine chemical building blocks into saleable products, either for final consumers or to other manufacturing. In 1994, energy intensity was 16.0 TBtu/$. When only basic chemicals are considered, the intensity is about twice as high.

Primary Metals. This industry includes the production of iron and steel (a Vision industry), aluminum (another Vision industry), and a variety of non-ferrous metals – lead, copper and zinc are the most important. The production of iron and steel falls into three sub-industries. *Integrated producers* transform iron ore into pig iron, then convert this to steel. The refined steel is cast or rolled into primary products such as sheet, bars, and billets. *Specialty steel producers* convert pig iron or steel into special products such as stainless and other alloy steels. *Mini-mills* produce primary steel products from scrap steel, usually in an electric arc furnace. Aluminum producers convert alumina (aluminum oxide) into aluminum metal using an electrolytic process. The major producers also convert ore, usually bauxite, into alumina, but that operation falls within the chemical industry classification. The intensity of this industry in 1994 was 15.3 TBtu/$.

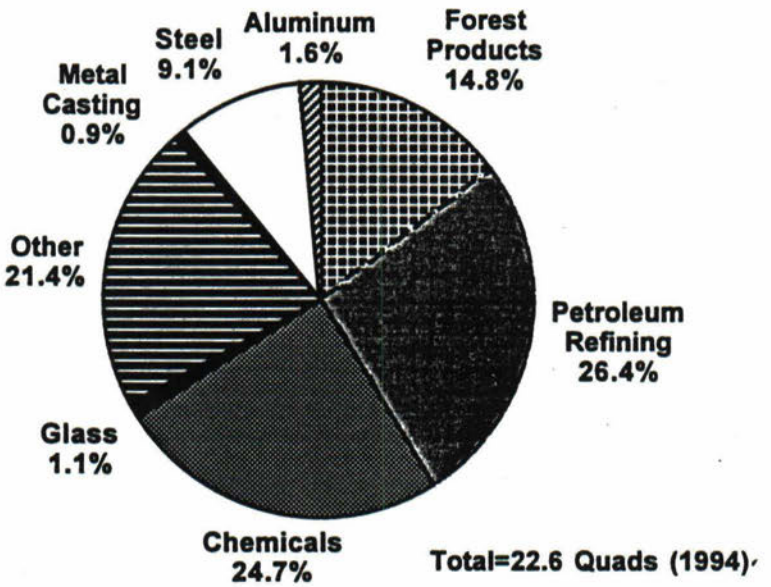
Stone, Clay and Glass Products. "Nonmetallic Mineral Products," under NAICS, includes cement, glass (a Vision Industry), bricks, lime, and other stone and ceramic products. Pyroprocessing, or the application of heat to assure a chemical reaction, is required in most of these subindustries, which is what makes them so energy-intensive. Cement and lime are formed at high temperatures in a kiln; glass is produced by melting silica sand; bricks, china and pottery are just clay until fired. The intensity of this industry is 13.3 TBtu/$.

4.1.1.3 A Continuing Stream of New Technologies

We assess qualitatively, again through the use of illustrative examples, the contributions that R&D might also make to reducing greenhouse gas emissions over a longer time frame. We describe R&D efforts that can lead to advanced technology offering energy-intensity and greenhouse gas emissions reductions beyond those described in the efficiency and high-efficiency/low-carbon cases, accompanied by rough quantitative estimates where possible. In this portion of the discussion, we again focus on the energy-intensive industries and on cross-cutting technologies. Input for the R&D assessment was sought from technology experts, particularly the OIT Industry of the Future teams and their industry and laboratory partners.

It is worthwhile to think of these more advanced technologies as the source of future emissions reductions *if* the pipeline of R&D is kept full and productive over the entire time horizon. Technology that is currently available to contribute to reduced energy use and emissions exists because R&D in the past is now paying benefits in the form of new technology. If there are to be future benefits, this pipeline must remain full. R&D focusing on efficiency improvements and carbon emissions reductions is needed to generate the new technologies of the future.

Figure 4.1 Share of Energy-Intensive Industries in Manufacturing End-Use Energy: 1994



4.2 ENERGY EFFICIENCY EMISSIONS REDUCTIONS

The LIEF model contains conservation supply curves for various industries that correlate energy conservation investment as a function of energy prices. These curves have been calibrated to historical industry data using an implicit Capital Recovery Factor (CRF) of 33%. CRFs and associated discount rates at this level or higher – representing a requirement that these investments pay back the capital outlay within a few years – have been found to characterize much of the decision-making in industry on investments in energy-efficiency technologies and on similar investments. At the same time, firms have another class of investment decisions – termed "strategic" investments – that are

characterized by a lower CRF or discount rate (i.e., the initial investments are allowed to pay back over a longer period) (see Ross 1990). One way, then, to simulate an increased investment in energy-efficient technology is to postulate a policy or set of policies that would lead industry to apply something like this more "strategic" discount rate to energy-efficiency investments. This effect could be induced via policies that served to decrease the first cost of such investments or that resulted in increased annual cost savings.

Another way to simulate such an increase in technology investment is to directly increase the factor that represents the penetration rate of new technologies. The penetration rate parameter in LIEF provides a measure of the rate at which industry adopts conservation projects. Firms do not immediately adopt all technologies that meet their criteria for cost-effectiveness and other factors – delays may represent a lack of capital, other priorities for the use of available capital funds, scheduling concerns, or simply a lack of awareness of the technologies. The box to the right discusses some of the factors that may affect the adoption of new, more energy-efficient technologies and policies that could be used to influence them. An increase in this penetration rate reflects a higher priority placed on energy conservation by industry as well as better information dissemination (Ross et al. 1993).

Increasing the Use of Advanced, Energy-Efficient Technology in Industry

Many aspects of business decision-making may slow the adoption of energy-efficient technology. They include :

- ⇒ ***High capital intensity of process industry leading to slow capital stock turnover,***
- ⇒ ***Perceived riskiness of new technology,***
- ⇒ ***Lack of internal funding resulting in less capital for energy projects,***
- ⇒ ***Lack of information.***

Policies that might reduce these effects are:

- ⇒ ***Accelerated depreciation,***
- ⇒ ***Better demonstration and showcase efforts to prove technology reliability,***
- ⇒ ***Reducing first costs and/or achieving better performance through aggressive R&D,***
- ⇒ ***Rebates or tax credits,***
- ⇒ ***Information programs and energy management services,***
- ⇒ ***Regulation and efficiency standards,***
- ⇒ ***Pricing and fiscal policies,***
- ⇒ ***Other economic incentive programs,***
- ⇒ ***The exemplary role of governments.***

These policies can be interpreted as changing the effective or perceived hurdle rates for efficiency investments or increasing the old capital turnover and adoption rates for new technology.

We have used both of these factors to simulate the efficiency case and the high-efficiency/low-carbon case for the industrial sector. We assume that either the discount rate or the penetration rate is affected in the efficiency case, and that both may be affected in the high-efficiency/low-carbon case. Further details on how the models were used to simulate these cases are provided in Appendix D-1.

4.2.1 Business-as-Usual Case

Our business-as-usual (BAU) case is the AEO97 reference case. Under this case, national economic output, measured by gross domestic product (GDP) is projected to increase by 1.9% annually to the year 2010. Within this overall growth, the manufacturing sector growth rate is projected at 2.1% per year, with energy-intensive industries growing at half the rate of non-energy-intensive industries, 1.3 versus 2.6%. The leading growth sectors within manufacturing are projected to be industrial machinery, electronic equipment, and transportation equipment. Of all the manufacturing subsectors,

electronic equipment is expected to have the highest growth rate, twice that of the manufacturing sector as a whole.

Total energy intensity, to the year 2010, is projected to decline by 1.1% per year. Among industry sectors, the largest declines in total energy intensity are projected for the pulp and paper and glass industries, with the cement industry third. Electricity intensity is projected to decline by 0.5% overall but with considerable inter-industry variation. The largest decline, 1.1% in the pulp and paper industry, contrasts with an increase of the same magnitude in the iron and steel industry. The distribution of primary energy consumption among end-uses is expected to remain stable, with more than two-thirds of industrial sector use accounted for by manufacturing heat and power requirements and the remaining third split about equally among non-manufacturing heat and power applications and use as process feed-stocks. For manufacturing heat and power, the largest energy-consuming industries are petroleum refining, chemicals, and pulp and paper production. The long-term trend of declining energy intensity in manufacturing is expected to continue, representing an 18% decline in energy intensity between 1995 and 2010. This trend is due to both adoption of energy-efficient technologies *and* relatively lower growth rates in the more energy-intensive industries. The effects of industry mix shifting toward less energy-intensive industries is stronger than the efficient-technology effect on the overall rate of change in energy intensity.

The AEO97 reference case assumes that there are no changes in federal energy or environmental policies over the forecast period. To the extent that the NEMS model reflects recent historical trends in industrial technology R&D performance, availability, and introduction, current and future private and government R&D funding for new and emerging technologies consistent with recent history contributes to the reference case decline in energy intensity.

4.2.2 Efficiency and High-Efficiency/Low-Carbon Cases

The industrial sector forecasts for the efficiency and high-efficiency/low-carbon (HE/LC) cases use the AEO97 energy prices and macroeconomic activity forecasts as a starting point. We assume no changes in economic activity that might arise from changes in energy markets.[5] Moreover, we assume no changes in the energy prices that could occur under conditions of lower energy demand. Energy markets adjust to changes in demand. This means that reduced demand in the EFF and HE/LC cases would lead to lower energy prices, thereby reducing incentives for efficiency gains.

The efficiency case assumes that industrial firms apply a "strategic" discount rate (or hurdle rate) to energy-savings investments. We simulate this effect in LIEF by changing the Capital Recovery Factor (CRF) from 33% to 15% to reflect the lower hurdle rate. Not all cost-effective technologies are assumed to instantaneously penetrate the market. The HE/LC case is based on the assumption that the penetration rate of the technologies that are cost-effective under a CRF of 15% doubles on average.[6] The LIEF model penetration factor was set initially at 3%, roughly calibrated to the NEMS BAU. The NEMS model uses rates of capital stock turnover that are similar in magnitude. This implies that, in the high-efficiency/low-carbon scenario, some acceleration of stock turnover is expected. This could occur under policy incentives for early retirement or economic incentives attributable to the costs and performance of new process technology that would make old equipment economically obsolete earlier than has been the case historically.

Table 4.1 summarizes the results in the energy consumption levels forecast by the AEO97. The overall change in energy use between 1997 and 2010 is shown for the BAU case in the first two columns for fossil fuels and electricity use (including system conversion losses). Renewables, feedstocks and non-energy uses of petroleum (e.g. asphalt, waxes, lubricants, etc.) are also shown, but are unaffected by the LIEF analysis. The next two columns show the effects of the efficiency case and the HE/LC case, as forecast by LIEF, on the AEO97 BAU case. Figure 4.2 shows that the HE/LC case approaches zero

growth with energy use increasing by only 1.4 quads (4%) between 1997 and 2010, in spite of an output increase of 30% over the period.

Table 4.1 Industrial Energy Use: AEO97 Business-as-Usual Case, and Efficiency and High-Efficiency/Low-Carbon Forecasts by LIEF (Quads)

	AEO97		LIEF	
		BAU	Efficiency Case	HE/LC Case
	1997	2010	2010	2010
Electricity (incl. related losses)	11.3	13.2	12.2 (7.6%)	11.2 (15.2%)
Fossil Fuels	16.0	18.2	17.2 (5.4%)	16.3 (10.4%)
Subtotal	27.3	31.4	29.4 (6.5%)	27.5 (12.5%)
Renewables*	1.8	2.3	2.3	2.3
Petrochemical Feedstocks and non-energy uses of petroleum	5.3	6.0	6.0	6.0
Total	34.4	39.7	37.6	35.8

Note: Numbers in parentheses represent the percent reduction compared to 2010 BAU case.

* Expanded renewable use is considered in Section 4.3.

Figure 4.2 BAU Energy Use and Projected Efficiency Cases in 2010 (quads)*

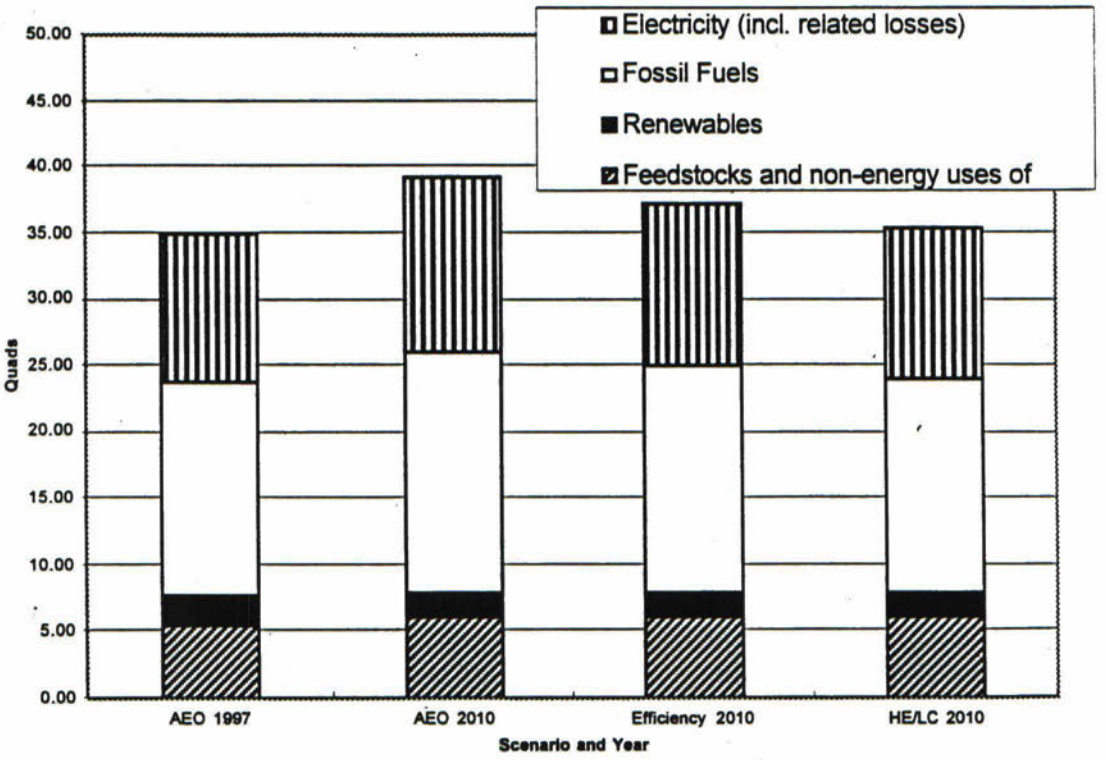


Table 4.2 shows the results of these analyses for ten major economic sectors of U.S. industry.[7] The results in Table 4.2 are expressed in terms of an additional annual percentage reduction in sectoral

energy intensity compared with the BAU case. The efficiency case reduces total energy intensity growth by an additional 0.5% per year. The HE/LC case reduces the growth in energy intensity by over 1% per year, relative to the BAU case, and reduces the growth in electricity use by more than 1% annually (1.3%).

Table 4.2 LIEF Results: Change in Energy Intensity, Annual Average Rate, 1997-2010, Compared with the Business-as-Usual Case (% change)**

	Efficiency Case CRF = 15% Penetration = Normal			HE/LC Case CRF = 15% Penetration = Double		
	Electric	Fuels	Total	Electric	Fuels	Total
Heavy Manufacturing	-0.36%	-0.28%	-0.31%	-0.70%	-0.60%	-0.63%
Pulp & Paper	-0.35%	-0.28%	-0.31%	-0.72%	-0.60%	-0.64%
Bulk Chemicals	-0.40%	-0.28%	-0.33%	-0.81%	-0.60%	-0.69%
Petroleum	-0.47%	-0.28%	-0.31%	-0.78%	-0.60%	-0.63%
Glass	-0.39%	-0.29%	-0.34%	-0.71%	-0.56%	-0.63%
Cement	-0.28%	-0.27%	-0.27%	-0.65%	-0.65%	-0.65%
Iron & Steel	-0.43%	-0.29%	-0.34%	-0.78%	-0.56%	-0.64%
Aluminum	-0.15%	-0.29%	-0.16%	-0.30%	-0.56%	-0.31%
Other	-0.35%	-0.28%	-0.31%	-0.75%	-0.63%	-0.69%
Light Manufacturing	-0.86%	-0.61%	-0.78%	-1.76%	-1.16%	-1.56%
Non-Manufacturing*	-0.67%	-0.67%	-0.67%	-1.26%	-01.27%	-1.27%
All Industry	-0.64%	-0.43%	-0.52%	-1.28%	-0.84%	-1.04%

*Non-manufacturing includes agriculture, construction, and mining (including energy extractions).

** Excludes renewables, feedstocks and non-energy uses of petroleum.

Table 4.3 translates these changes in energy intensity into percentage changes (reduction) in energy consumption in 2010, relative to the BAU case. In the HE/LC case, overall energy consumption decreases by more that 12% in 2010 relative to the BAU case, while the decrease in the Efficiency case is more than 6%. The results for individual industries vary; the declines in energy intensive industries are close to the average for all of industry, but non-energy intensive sectors show percentage declines of about twice that of heavy industry.

That the percentage reduction in energy use is higher in light industry stems from two reasons. The first is that energy is a very small part of the costs in these sectors so that energy efficiency investment is often overlooked. The LIEF model represents this by a large difference between the average light manufacturing plants and the most efficient ones. The high growth sectors in light manufacturing have relatively larger opportunities to make significant percentage reductions than do their energy intensive counterparts, who have already done so in response to rising energy prices in the 1970s. In addition, light industries' energy use is dominated by electricity. Electricity savings in light manufacturing comes largely from computer controls, motor systems, as well as contributions from lighting and HVAC that are similar to technologies discussed in the buildings chapter

The second is that the growth in output for light industry is much higher than for heavy industry. Output grows more than 80% by the year 2010 for light industry, but only 30% for heavy industry. As a result, in the BAU case, electricity demand nearly doubles for light industry and fossil fuel use

grows more than 60%. Fossil fuel demand for heavy industry only increased by 12% in the BAU case, while electricity demand increases by 48%.

The difference between light and heavy manufacturing is a major source of the difference in the energy savings (on a percentage basis) between fossil fuels and electric energy. One should note that, while these percentage savings vary, a significant portion of the energy savings in absolute terms still come from fossil fuel use reduction in heavy industry, e.g. fossil fuel reductions in heavy manufacturing is about 8% while the industry total for fossil fuels is about 12%.

Table 4.3 LIEF Results: Energy Savings in the Year 2010 Compared with the Business-as-Usual Case (% reduction)**

	Efficiency Case CRF = 15% Penetration = Normal			HE/LC Case CRF = 15% Penetration = Double		
	Electric*	Fuels	Total*	Electric*	Fuels	Total*
Heavy Manufacturing	4.6%	3.6%	4.0%	8.7%	7.5%	7.9%
Pulp & Paper	4.5%	3.6%	3.9%	9.0%	7.5%	8.0%
Bulk Chemicals	5.0%	3.6%	4.2%	9.9%	7.5%	8.5%
Petroleum	5.9%	3.6%	3.9%	9.7%	7.5%	7.8%
Glass	5.0%	3.7%	4.3%	8.8%	7.0%	7.8%
Cement	3.5%	3.5%	3.5%	8.2%	8.1%	8.1%
Iron & Steel	5.5%	3.7%	4.4%	9.6%	7.0%	8.0%
Aluminum	2.0%	3.7%	2.0%	3.8%	7.0%	4.0%
Other	4.4%	3.5%	3.9%	9.3%	7.9%	8.5%
Light Manufacturing	10.6%	7.6%	9.6%	20.4%	14.0%	18.3%
Non-Manufacturing*	8.3%	8.3%	8.3%	15.1%	15.2%	15.2%
All Industry	8.0%	5.4%	6.6%	15.30%	10.4%	12.5%

These numbers are based on electricity system-average energy loss from the business-as-usual case.

*Non-manufacturing includes agriculture, construction, and mining (including energy extraction).

** Excludes renewables, feedstocks and non-energy uses of petroleum.

Table 4.4 illustrates how the energy use by fuel type is affected in each scenario. Natural gas use, the dominant fuel use by industry, declines the most in absolute terms. Petrochemical feed stocks, other non-energy uses of petroleum, and renewables are assumed to be unaffected in the efficiency and high-efficiency/low-carbon cases and do not contribute to the carbon emissions.

Table 4.4 Change in Industrial Energy Use by Fuel Type

	AEO		Efficiency	HE/LC
	1997	2010	2010	2010
Natural gas (billion cu ft)	9,914	11,103	10,303	9,564
Coal and coke (1000 short tons)	104,716	113,741	10,551	97,976
Liquid fuels - incl. LPG (1000 bbl)	695,160	697,300	647,090	600,648

Petrochemical feed stocks & other petroleum (1000 bbl)	925,536	1,180,979	1,180,979	1,180,979

Table 4.5 provides carbon emissions estimates for 2010 in metric tons. Because LIEF does not model fossil fuel choice, estimates of carbon reductions are based on the fossil fuel mix and emission factors in NEMS. For fossil fuels, there are two ways to compute carbon emissions. The first is to assume that efficiency affects fuel reductions through the average fuel mix. The second is to assume that most energy-efficiency reductions operate on the margin (i.e., they affect those fuels that constitute the growth in the BAU forecast).

Table 4.5 Carbon Emissions Estimates (MtC per year)

	AEO97		Efficiency Case	HE/LC Case
	1997	2010	2010	2010
Electricity	172	213	204 (4.5%)	186 (12.7%) *
Fossil Fuels	311	335	317 (5.4%)	300 (10.4%)
Industry Total	482	548	521 (5.1%)	486 (11.3%)

*A portion of the reduction in carbon emissions associated with the high-efficiency/low-carbon case is due to changes in the electricity generation mix prompted by the charge of $50/tonne of carbon (see Chapter 6). Numbers in parentheses represent the percent reduction compared to 2010 BAU case.

An examination of the change in fossil fuel mix in industry in the AEO97 found that no fuel's share changed by more than 1%. Consequently, using the average industrial fossil fuel mix from the AEO97 is a reasonable approach to compute the change in greenhouse gas emissions. However, the electric utility industry shows an increasing share of natural gas. Therefore the carbon reductions for electricity use in Table 4.5 are based on the marginal carbon emission rates, rather than the average (see Chapter 6 for more details).

These overall carbon reductions are translated into industry-specific carbon reductions in Table 4.6. Heavy manufacturing contributes about one-third of the savings in both the efficiency and HE/LC cases. The large contribution of carbon savings from light industry comes mostly from electricity efficiency. Electricity use in this sector is growing rapidly – almost doubling – in the BAU case.

Table 4.6 Industry-Specific Reductions in Carbon Emissions (MtC per year in 2010)

	Efficiency			HE/LC		
	Electric	Fuels	Total	Electric	Fuels	Total
Heavy Manufacturing	2.1	7.1	9.2	5.9	14.8	20.6
Pulp & Paper	0.3	1.1	1.5	1.0	2.3	3.3
Bulk Chemicals	0.7	1.5	2.2	1.9	3.2	5.1
Petroleum	0.3	2.5	2.7	0.6	5.2	5.8
Glass	0.1	0.2	0.2	0.2	0.3	0.5
Cement	0.0	0.2	0.3	0.1	0.5	0.6
Iron & Steel	0.4	1.2	1.6	1.1	2.3	3.4
Aluminum	0.1	0.0	0.2	0.4	0.0	0.4
Other	0.2	0.4	0.6	0.6	0.9	1.5

Light Manufacturing	6.3	5.2	11.5	17.8	9.7	27.4
Non-Manufacturing*	1.3	5.7	7.0	3.4	10.4	13.8
Total	9.6	18.1	27.7	27.0	34.9	61.9

* Non-manufacturing includes agriculture, construction, and mining (including energy extraction).

4.2.3 Comparison with the NEMS model

The NEMS model provides a different approach and perspective on the EFF and HE/LC cases. The NEMS model uses a stock turnover approach to project the change in energy use. New technology is projected to be more efficient; thus, as capital is replaced, the overall energy requirements in the industry decline. To compare the scenarios, the NEMS industrial model was run under alternative assumptions and compared to those corresponding industry sectors in LIEF (see Table 4.7).

When the retirement rate of capital is doubled in the NEMS industrial model, the decline in total energy use ranges from 1-8%, depending on the sector. On the other hand, when the performance of new technology is assumed to double (i.e., the relative energy intensities of new technologies in NEMS decline twice as fast as in the BAU case), even larger reductions in energy use are achieved for all sectors except cement and steel. These parametric variations in the NEMS model illustrate, in rough magnitude, what rate of technology improvement or stock turnover would be consistent with the EFF and HE/LC case. For example, only in the iron and steel industry does the doubling of the retirement rate result in energy savings comparable to those in the HE/LC case; for all other industries, it would require more effort than simply doubling the capital stock turnover to achieve comparable savings. For aluminum and glass, the energy savings resulting from the NEMS run that doubles technology performance are higher than the energy savings in the HE/LC case, suggesting that for these sectors more rapid technology development is an important part of future savings. This is particularly true of the aluminum sector.

Table 4.7 Comparison of Year 2010 Total Energy Savings Relative to BAU in the NEMS and LIEF Models

	LIEF		NEMS	
	Efficiency Case	HE/LC Case	Doubled Retirement	Doubled Technology Performance
Paper	3.9%	8.0%	4.9%	7.5%
Chemicals	4.2%	8.5%	1.3%	5.0%
Glass	4.3%	7.8%	3.6%	9.9%
Cement	3.5%	8.1%	5.7%	3.6%
Iron and Steel	4.4%	8.0%	8.2%	2.9%
Aluminum	2.0%	4.0%	1.2%	7.8%

4.2.4 The Historical Context of Energy Efficiency in Industry

Over time, both the "what" and the "how" of industry output changes. Buggies and whips have disappeared, but automobile production has taken their place. And while the Model T was mass-produced, today's methods of production are only vaguely reminiscent of Henry Ford's assembly line. Energy use in manufacturing and other industry sectors has changed due to both product and process transformation. Energy use changes occur because of energy-efficiency improvements over time as well as changes in the mix of industries. Rough approximation of the importance of these two factors

indicates that efficiency accounts for about two-thirds of the change, while the shift in the mix of industries accounts for about one-third. Put into historical perspective, forecasts of energy use and energy intensity changes used for this analysis are modest changes and, we believe, more than just possibilities. With appropriate and effective policy measures to accelerate the adoption of technologies that are currently, or will soon be, available, the efficiency gains and energy and carbon savings projected could easily be achieved.

A study published by DOE (1995) illustrates how rapidly energy intensity in the industrial sector can decline. Between 1972, the last full year prior to the effect of the first oil price shock, and 1985, when energy prices fell, the rate of decline in energy intensity in industry was 2.74% per year. During the period of the most rapid decline, from 1975 to 1983, industrial sector energy intensity fell by 3.12% per year. These numbers show that, when industry has a major incentive to reduce energy use, it will do so. By the same token, when the incentives are reduced, so are the improvements. Between 1984 and 1991, energy intensity in the industrial sector declined by less than 1% per year, and in four of these years, the intensity actually increased.[8] Of the energy savings that occurred in the industrial sector between the mid-1970s and the early 1990s, this report suggests that about one-third of the total was attributable to compositional shifts (i.e., shifts from high energy-intensive industries to industries with lower energy intensity). The remainder was attributable to reductions in energy intensity within industries.

In the BAU forecast, total energy intensity declines at about 1.1% per year, with more than half of this decline (0.6%) attributable to projected composition effects. If one takes the efficiency component of the total energy intensity decline forecast for the BAU case (0.5% per year) and adds the additional 0.85% per year from the high-efficiency/low-carbon case, the HE/LC case has a rate of energy intensity decline (1.35%) that is slightly below the historical rate over the period 1972-1991 (1.89%).

4.2.5 The Costs of Achieving the Efficiency and HE/LC Cases

The LIEF model conservation supply curves can be used to compute the investment implied by the forecast energy reductions. These estimates, shown in Table 4.8, are the additional investment required to achieve the energy savings presented above. Due to the long-lived nature of industrial capital goods, this cumulative investment in more efficient and productive industrial plant and equipment continues to generate energy and costs savings, relative to the base case, after the 2010 time horizon.

LIEF projects that this level of investment is profitable with the BAU forecast energy prices and a CRF of 15%. The energy savings provides about a seven-year payback on the initial investment. The magnitude of the up-front costs, which are paid back only over time, may be an issue in designing policies to spur this enhanced technology penetration.

To put this level of investment in energy efficiency into context, we compare it to total investment in manufacturing. If the cumulative investment in energy efficiency is spread out evenly over the 13-year time period, the HE/LC case would require a $3.6 billion increase in annual investment in efficiency technology. In 1992, total investment in manufacturing (not including agriculture, construction, and mining) was $110.1 billion (1995$). Thus, the incremental annual investment needed to achieve the HE/LC case represents a 3.3% increase over the level of manufacturing investment for 1992.

Table 4.8 Cumulative Incremental Investment (1998-2010) for Energy Efficiency Implied by the LIEF Model to Achieve the Forecast Energy Reductions (billions of 1995$)

	Efficiency Case	HE/LC Case

Fossil Fuels	7.4	15.2
Electricity	15.8	32.0
Total	23.2	47.2

Historical behavior with respect to energy efficiency investments has been characterized by implicit marginal discount rates equivalent to 33% capital recovery. The efficiency case is based on the notion that the marginal return on energy efficiency will be closer (or equal) to a *strategic* discount rate, represented here as a 15% CRF. For example, this translates to a marginal real return of 12.5% per year on a 15-year investment, which we will use for illustrative purposes. It is from this perspective that the efficiency case reflects 'cost-effective' investments. The 'last' investment will produce cost savings that will provide a return of 12.5%; other investments will generate higher returns. On average, the return will be higher than the marginal, or 'last', energy-efficiency project.

Table 4.9 shows the private investment cost of an investment in efficiency in a *single year* , compared to the value of the energy savings that would continue to accrue thereafter. The first line in the table is the incremental investment in the last year of our forecast, 2010. The second and third lines are the change in consumption and expenditure of energy for that year, which are negative since energy consumption is reduced. One can see that investments generate annual savings of about a third of the initial outlay. This is an average return that is quite a bit higher than the assumed marginal return of 12.5%. Recall that the marginal return is the 'last' cost-effective investment, which just pays for itself at the 12.5% rate.

Table 4.9 also shows the total energy savings and direct private costs of the scenario. These costs are generated using the cost of conserved energy (CCE) method detailed in Appendix A-1.3. For the efficiency scenario the energy savings exceed the direct private investment costs by $4 billion. The HE/LC scenario has energy savings in excess of direct investment costs of $7 billion.

Table 4.9 Net Costs of Private Investment for Energy Savings in the Efficiency and High-Efficiency/Low-Carbon Cases (millions of 1995$)

		Efficiency		HE/LC	
	Units	Fossil Fuels	Electric (End-use)	Fossil Fuels	Electric (End-use)
Investment in 2010	M$	$800	$1,700	$1,500	$3,200
Annual Energy Reduction	TBtu	94	47	178	82
Annual Reduction in Energy Costs	M$	$300	$600	$600	$1,100
Total Energy Redirection	TBtu	900	336	1800	685
Total Investment Cost	M$	$1,100	$1,800	$2,400	$4,100

Note: Costs are based on the annualized costs over the time period, not the cummulative investments.

We believe that most, if not all, of the difference between the observed behavioral CRF of 33% and the 15% CRF is due largely to factors that preclude firms from using these lower marginal rates for energy-efficiency investments, such as transaction costs, agency costs, the lack of information or the cost of acquiring it, perceived risk, etc. However, policies will be required to remove these factors and shift investment behavior to prioritize energy efficiency the same as other corporate investment. These policies will have a public cost.

The HE/LC case also focuses on 'cost-effective' investment under the same notion of these lowered, strategic, marginal rates of return. However, one important difference in the HE/LC scenario is that a higher adoption rate is assumed. While some additional penetration, relative to the BAU, may be accounted for by further transformation of the market of energy-efficient practices we feel that some accelerated retirement may also take place. When the economic losses of accelerated retirement are accounted for, this implies that, at the margin, all investments are not likely to be cost-effective at our

assumed 15% CRF. Since we do not have a model to account for this potential early retirement and the economic losses, we must caveat our estimates of investment. The energy savings from the HE/LC scenario in Table 4.9 does not change, but the investment cost may be understated by the amount of loss due to any early retirement that may occur. Because the net benefit is still greater than the annualized investment we calculate, then unaccounted costs may be about twice our estimated energy-efficiency investment, with the HE/LC scenario remaining 'cost-effective' on average.

A carbon-based fuel price increase was considered and simulated using LIEF for a number of carbon shadow prices. Energy price increases alone do not have a very dramatic effect on energy use in the LIEF model. While they do have some affect on the options to reduce energy use, they have no endogenous affect on the rate of penetration of new technology in the model. For example, a $50 shadow price for carbon increases shifts the "ideal" energy-output ratio by only 8.5% for electricity and 5% for fossil fuel. The gap between the ideal and actual energy-output ratios is a measure of the conservation potential for the sector. Under the BAU case, this gap is 3.8% for electricity and 4% for fossil fuel. Under the EFF case, this gap is 27.6% for electricity and 15.3% for fossil fuels. Under the $50 shadow price case, the gap is 9.5% for electricity and 7% for fossil fuels. To achieve the same ideal energy-output ratio as the HE/LC case would require a shadow price of $250 for fossil fuels and $300 for electricity. Table 4.10 shows the carbon reduction and the percentage reduction in electricity and fossil fuels that result from simulation of different carbon shadow prices.

Table 4.10 Effect of Different Carbon Shadow Price Simulations on Electricity and Fossil Fuel Reductions

Shadow	Electricity		Fossil Fuels	
Price of Carbon	% of BAU	Carbon Saved	% of BAU	Carbon Saved
25	98.4	3	99.0	3
50	97.1	6	98.2	6
100	95.1	10	96.9	10
200	92.2	16	94.8	17
300	90.1	20	93.3	22
400	88.6	23	92.3	26

The HE/LC case reduces electricity to 85.2% of the BAU case and fossil fuel to 92.5%. The energy/carbon savings in the table would be larger if these higher prices systematically affect the penetration rates of new technology, which one would expect. However, penetration rates are currently parametric in LIEF, and since we have very little information about how price changes affect penetration rates, we have not altered that parameter for this exercise. Given the belief that the rise in prices would increase penetration, the estimates of energy and carbon savings from LIEF would represent an upper bound on the required carbon tax or a lower bound on the savings.

The implications of the 'standalone' analysis of carbon shadow prices is that a variety of polices well beyond a carbon permit charge would be required to achieve the savings projected in these scenarios.

4.3 ADDITIONAL EMISSIONS REDUCTIONS FROM INDUSTRIAL LOW-CARBON TECHNOLOGIES

4.3.1 Introduction and Summary

Industrial low-carbon technologies reduce greenhouse gas emissions through means other than traditional energy efficiency. We separate low-carbon technologies into three types:

- *Power-system efficiency maximization* (PSEM) technologies: such technology systems comprise mainly existing technologies assembled in an innovative way so as to maximize energy efficiency at certain types of locations for particular industries' heat and power needs.

- *Fuel-switching* technologies: these reduce carbon emissions by using low- or no-carbon fuels instead of high-carbon fuels. Many energy forecasting models, including LIEF and NEMS, incorporate switching from oil, coal or electricity to less carbon-intensive gas. They do not, however, generally incorporate switching to new advanced biomass or other new renewable technologies. Both of these low-carbon technology types are often grouped with energy-efficiency technologies. We separate them from efficiency technologies in this chapter because their additional contributions to carbon reductions are not generally included in traditional energy models.

- *Low process carbon* technologies: this type reduces or avoids the emission of CO_2 and other greenhouse gases from industrial processes, not from combustion. They are clearly not included in energy models. We have found that most of these emissions are non-CO_2 greenhouse gases. Because these emissions do not involve energy, they have not been included in energy-focused carbon analyses. However, as shown in Section 4.3.4, these non-energy emissions account for a third of total greenhouse gas equivalent emissions in the industrial sector. (Industrial CO_2 emissions from energy are projected to be 482 MtC equivalent in 1997 (EIA 1996) and non-energy-related carbon equivalent emissions were 244 MtC equivalent in 1994).

This section provides examples, rather than a comprehensive survey, of low-carbon technologies. Such a survey would have been difficult because, unlike traditional energy-efficiency technologies, these technologies do not have a long history of being analyzed from the perspective of reducing carbon equivalent emissions. However, as shown in Table 4.11, just these examples showed great potential reductions. Thus, a comprehensive survey of these technologies is an important area for future analysis in the industrial sector. Note that the carbon reductions presented are in addition to the carbon savings of Section 4.2.2. Some of these technologies also feature carbon reductions due to traditional energy efficiency. We used the energy-efficiency projections for the various traditional markets presented in Section 4.2.2 to subtract these carbon savings from the technologies' estimated overall carbon reduction. Greenhouse reductions from "low process carbon" technologies are not included in this report's summary tally of carbon reduction potential because of the report's focus on combustion-related emissions.

In the following sections, we provide examples of the three types of low-carbon industrial technologies. The Advanced Turbine System (ATS) described in Section 4.3.2 is an example of a PSEM technology. It is a combined heat and power (CHP) system that replaces grid electricity and steam from industrial boilers with a highly efficient on-site natural gas-fired turbine that generates both electricity and steam. The carbon reductions from on-site CHP were not included in Section 4.2.2. The ATS may also further maximize system efficiency by replacing electricity used to drive motors that drive equipment with direct power for the equipment. Even when used as a power-only technology, ATS reduces carbon emissions because it is located on-site – avoiding transmission and distribution (T&D) losses. The ATS is also a fuel-switching technology if it replaces high-carbon fuels such as coal used in the boilers with natural gas or no-carbon biomass gas.

Section 4.3.3 gives an example of a fuel-switching technology. Black liquor and biomass gasifiers integrated with combustion turbines replace biomass boilers and grid electricity. In the near and medium time frame, biomass and black liquor gasification technologies provide the option of switching from a high-carbon to a "no-carbon" fuel. Note that the advanced technologies described in Section 4.3.3 are also PSEM technologies because they replace inefficient biomass boilers and grid electricity with biomass gasification combined heat and power systems.

Section 4.3.4 describes two low process carbon technologies. The first, the advanced aluminum production cell, shows that for some industrial processes there are multiple opportunities for reducing carbon equivalent emissions. The second involves the substitution of waste products – fly ash and blast furnace slag – for a portion of the calcined cement clinker intermediate product in cement production. Both of the examples reduce carbon through improved energy efficiency in addition to reducing or eliminating carbon equivalent process emissions.

A summary of the carbon reductions from these technologies is given in Table 4.11 for both the efficiency and the high-efficiency/low-carbon (HE/LC) cases.

Table 4.11 Examples of Additional Carbon Equivalent Reductions by 2010 Resulting From Low-Carbon Technologies* (MtC equivalent)

	Efficiency Case	High-Efficiency/Low-Carbon Case
Power System Efficiency Maximization Technology (PSEM)		
Advanced Turbine Systems	5-7	14-24
Fuel-Switching Technology		
Forest Products – IGCC	5	10
Low Process Carbon Technologies		
New Aluminum Production Cell	0–1	2–4
Cement Clinker Replacement	-	1–2
Total	**10–13**	**27-40**

*These reductions are not accounted for in Section 4.2.2.

4.3.2 Power System Efficiency Maximization Technologies

Power-system efficiency maximization technologies are grounded in the second law of thermodynamics. PSEM technologies take advantage of the fact that waste heat is always produced. Such systems also reduce or avoid extra energy conversion and process steps that waste energy. The key to PSEM is the system. Instead of using a separate technology for electricity for the company's PCs, building heating and cooling, process steam and electricity for motors, a company could use a PSEM technology. For example, the Advanced Turbine System (ATS) described in Section 4.3.2.1, could provide all these system needs. The ATS could provide reliable high-quality electricity to the PCs; ATS steam coupled with a heat exchanger could provide building heating and cooling and steam for process uses; and the turbine could be hooked directly to the drive shaft of the machine formerly driven by a motor that used grid electricity. District energy sites, where businesses group together and share electricity and steam from the same turbine, are also examples of PSEM technologies in the industrial sector. A recent study (IDEA 1997) indicates that, of the nearly 6000 current U.S. district heating installations generating more than 1.1 quads, 8% are classified as industrial. We expect that well-crafted policies to increase energy efficiency and reduce carbon will spur creative uses of both heat and power in such systems. In addition to multiple incremental improvements, we expect that some PSEM will be breakthrough technologies.

4.3.2.1 Advanced Turbine Systems (ATS) for Industrial Applications

Advanced Turbine Systems (ATS) are high-efficiency, next-generation gas turbines that produce less carbon per kWh than technologies used in conventional power markets. When commercialized in the year 2001, the emissions of CO_2 from ATS are projected to be 600 lb/MWh, 29–73% lower than conventional technologies (see Figure 4.3).[9] ATS is one of the major low-carbon technologies for the industrial sector between now and 2010 because it is a natural gas-fired turbine that cogenerates electricity and steam. The ATS's high energy efficiency stems from multiple incremental improvements applied in a novel manner.[10] Cogenerated steam displaces industrial steam boilers and their associated emissions. The steam can also be put back into the system for additional electricity generation. Further emissions reductions are due to the ATS being gas-fired and located on-site.

Although not included here because of possible double counting with Section 4.3.3.1, the ATS technology is also well suited for biomass and landfill gas fuels. The ability of ATS to burn biomass without turbine fouling and maintenance problems is being explored via new turbine materials, including ceramics and single crystal and directionally solidified turbine blades. Substantial reductions in greenhouse gas emissions will result if ATS is fired with biomass fuel – especially in combined heat and power mode. It will require the evolution of a biomass fuel supply infrastructure, or its penetration will be limited to those industries that already have access to biomass fuels, such as forest products and some food processing sectors. We provide an example of biomass-based cogeneration in the paper industry in Section 4.3.3.

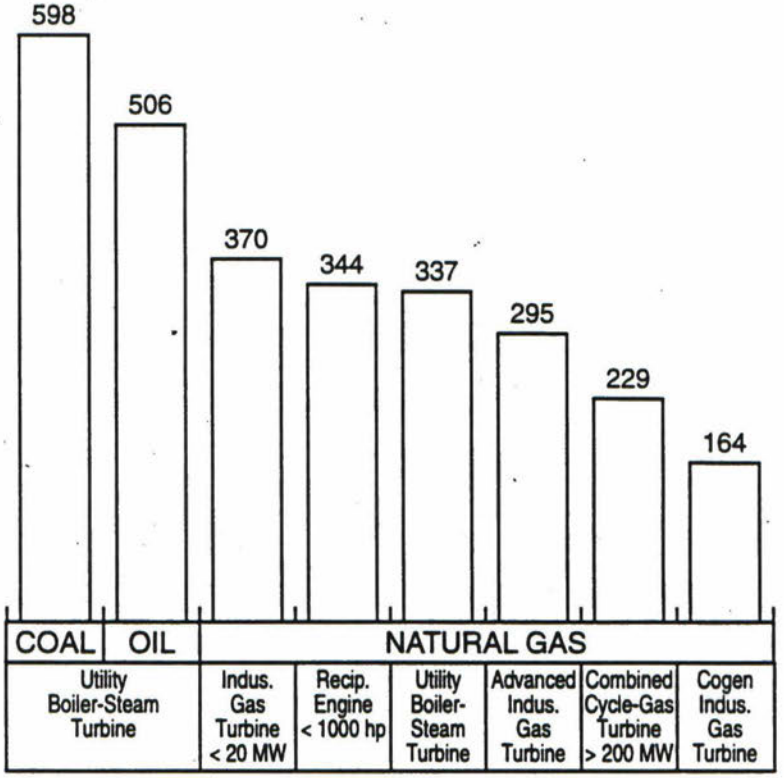
We divided the ATS "markets" into three types. The first type includes high electricity-to-thermal (E/T) ratio "power only" opportunities. These are sites where there is little or no steam demand and most of the steam from the ATS is fed back into electricity generation. The second type, "combined heat and power" (CHP), includes sites where ATS provides both steam and electricity needed on-site. The third type is a "new steam" market, where the steam and electricity needs vary.[11]

This "new steam" market is a new market not included in most energy forecasting models. It is new CHP capacity in which power and heat are not balanced and where the desire to generate electricity may be more important than getting the perfect steam match. Unlike traditional cogeneration equipment that is only efficient at a particular E/T ratio, ATS CHP systems run at high efficiency in a variety of steam and electricity configurations. As detailed in Appendix D-3, this market will spur creative uses of both heat and power. For analytic purposes, we have analyzed the "new steam" market as if it were two separate CHP and power-only markets. We decomposed new steam into traditional CHP (cogeneration assuming heat/power balance) and Power-Only (PO):

$$New\ steam = a*CHP + b*PO$$

While some sector-specific studies (Appendix D-3) show a and b values around 0.5 for the entire market, the values of a and b are not well known except that they are both significant. As detailed in Appendix D-3, this decomposition also simplifies the calculation of the carbon offset. Figure 4.4 depicts simplified diagrams that allow comparison of the following: (1) a traditional steam boiler system, (2) a steam boiler that produces power using an ATS, (3) an ATS used for combined heat and power, and (4) an ATS used for power only. There are many other combinations, such as a turbine with a recuperator not shown here.[12]

Figure 4.3 Carbon Equivalent Emissions for Several Electric Generation Technologies (pounds per MWh)



Source: Gas Research Institute (1994) and Onsite Energy (1997)

Considering the large markets not yet served by this type of CHP, industry experts predict that the availability of advanced turbines will double the growth rate of new CHP capacity (Carroll 1997). This growth will greatly exceed the historic industrial market penetration of cogeneration,[13] particularly for smaller power technologies used to meet internal energy requirements. Under the efficiency or high-efficiency/low-carbon scenarios, the change in the market will occur even faster. Relatively higher prices for carbon-based fuels will encourage dispatching of electricity from low-carbon fuels, reform of environmental permitting, and utility regulations and will thus accelerate the replacement of boilers by on-site ATS cogeneration. The turbine's low installed costs, low NO_x emissions, and ability to generate electricity when steam is not needed will also contribute to the rapid growth of this new steam market.[14,15]

Table 4.12 shows the contributions of these two "markets" to the total carbon reductions. As described in Appendix D-3, the power-only carbon reductions are much smaller because we assume that the power being displaced is also quite efficient.[16] Thus, the ATS only takes credit for carbon reductions due to avoidance of transmission and distribution losses (7%). In addition, we assume the grid electricity (see utility chapter for details) and the steam boilers displaced have higher carbon emissions than those displaced in the efficiency case. For both cases, we subtracted the same traditional cogeneration that is contained in the NEMS BAU.

Figure 4.4 Simplified Diagrams of Advanced Turbine Systems in Power-Only and Cogeneration Mode Compared to Steam Boiler

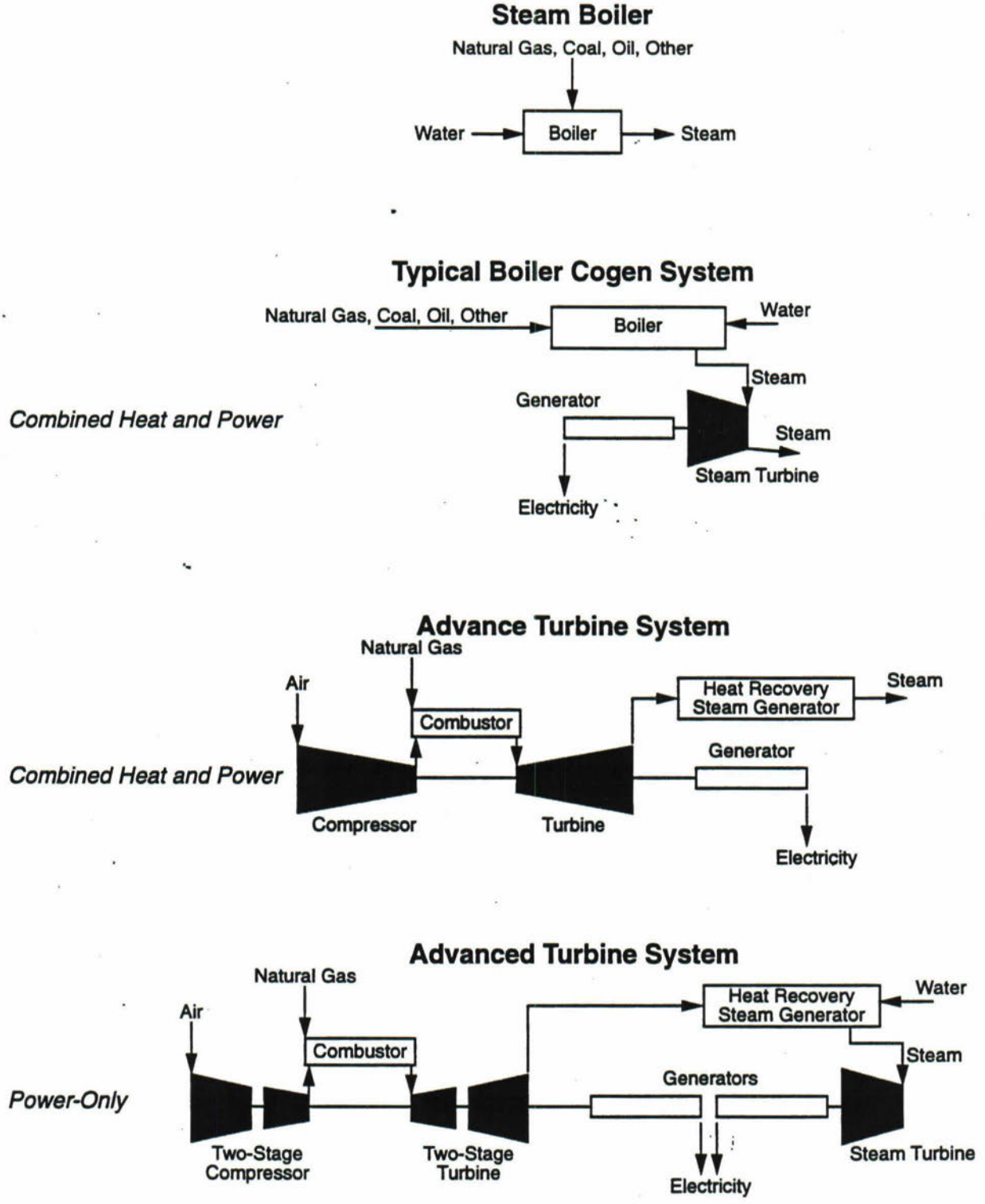


Table 4.12 Calculation of 2010 ATS Carbon Savings (MtC) and Corresponding ATS Electricity Generation (TWh)**

	Combined Heat and Power*	Power Only	Total
Efficiency	4-6 (29-59)	1 (120)	5-7 (150-180)
High-Efficiency/Low-carbon	12-21 (60-120)	2 (220)	14-24 (280-340)

Numbers may not add up exactly due to rounding. TWh shown above in parentheses.

* Excludes carbon reductions and electricity generation from traditional cogeneration that is contained in the NEMs BAU case as well as forest products biomass cogeneration which is considered in Section 4.3.3. Other ATS markets where ATS electricity generation did not result in substantial carbon savings were also excluded.

** See Table D.3-4 for details.

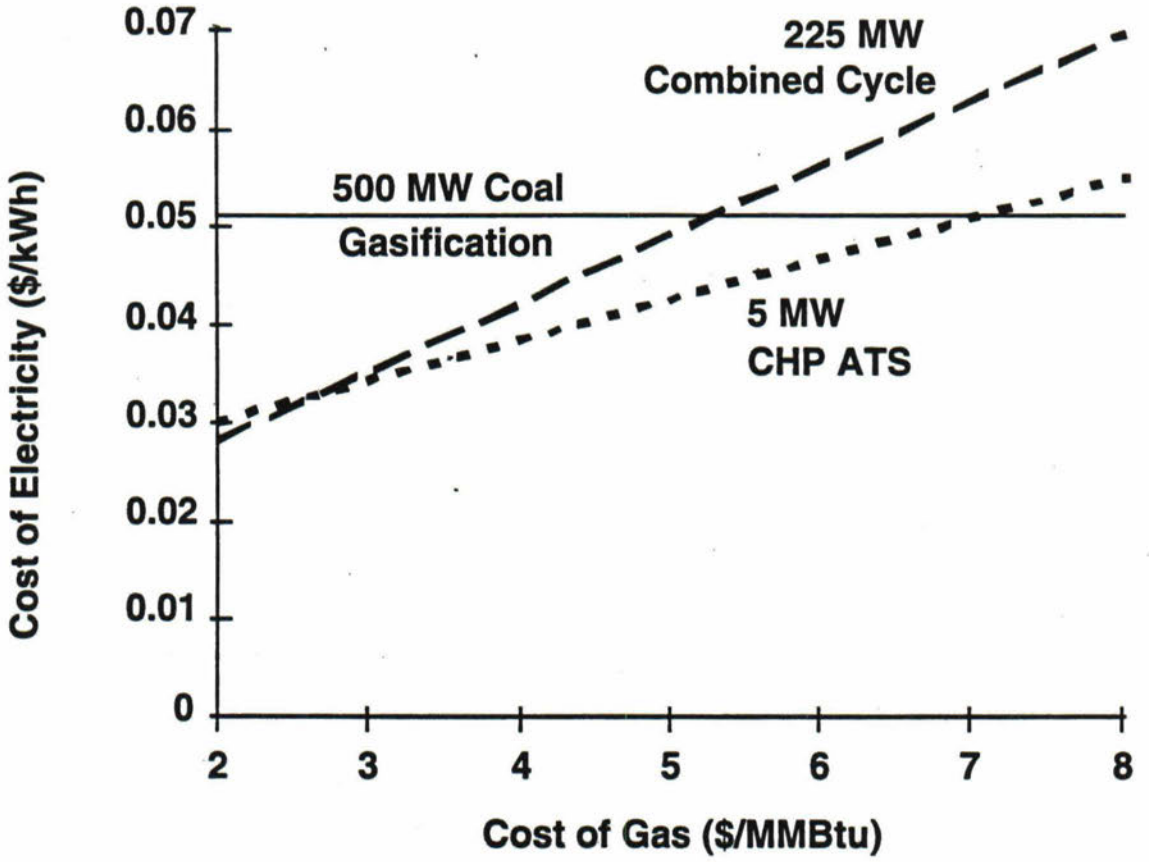
We estimate ATS carbon reductions of 5-7 MtC equivalent for the efficiency case (see Appendix D-3). This corresponds to an electric capacity of 23-27 GW and requires 0.5 TCF of additional natural gas (5% of 2010 BAU industrial demand) due to fuel switching from oil and coal biolers. For the high-efficiency/low-carbon (HE/LC) case we assume, similar to Section 4.2.2, that the penetration of ATS in these markets will double over that of the efficiency scenario. In addition, we assume the grid electricity (see utility chapter for details) and the steam boilers displaced have higher carbon emissions than those displaced in the efficiency case. This results in an ATS HE/LC carbon reduction of 14-24 MtC equivalent per year by 2010. This corresponds to an electric capacity of 42-51 GW and 1.0 TCF of additional natural gas (11% of projected BAU 2010 industrial demand).

Most of the carbon reduction comes from the fact that the ATS has a combined efficiency that is 5-10% greater than boilers. This greater efficiency also results in electricity costs that are 10% lower than current generation systems. Equipment costs are projected to be approximately $350/kW ($1.8M for a 5 MW unit) for a recuperated simple cycle unit and somewhat higher for a combined cycle unit. The major turbine manufacturers in the U.S. project that ATS will have captured 15% of U.S. power generating capacity by 2010 (Major 1997). In power-only mode, the system will be competitive against electricity prices of $0.03-0.04/kWh (Brent and Davidson 1996, Hoffman 1997). More specifically, Figure 4.5 shows that the ATS is the least-cost option for a wide range of gas and electricity prices, but it does not compete favorably with very low gas prices (where the large combined cycle turbine is less expensive) or with high gas prices (where coal gasification systems are less expensive). Note that the breakeven point between ATS and combined cycle systems is very close to the projected price of natural gas to industrial consumers ($2.60 per million Btu) in the AEO97 BAU case.

Even though the ATS is 2-3 years from being commercialized, some of the ATS manufacturers already have significant orders for ATS (Parks 1997). Since the average order/delivery time is 18 months, this means that the ATS customers are willing to wait at least 18 additional months for a superior technology. This suggests that the ATS may penetrate far more rapidly than traditional energy technologies.

In addition to carbon reduction, these turbines have other environmental benefits. ATS's low-emission combustion systems generate less than 9 ppm NOx through lean premix combustion and less than 5 ppm NOx with catalytic combustion, with no other major pollutants. When deployed in 2001, ATS systems, per MW, will produce 77–95% less NOx per megawatt than competing power generation technologies (Major and Davidson 1997b).

Figure 4.5 Electric Generation Cost Comparison



Source: Onsite Energy (1994)

4.3.3 Fuel-Switching Technologies

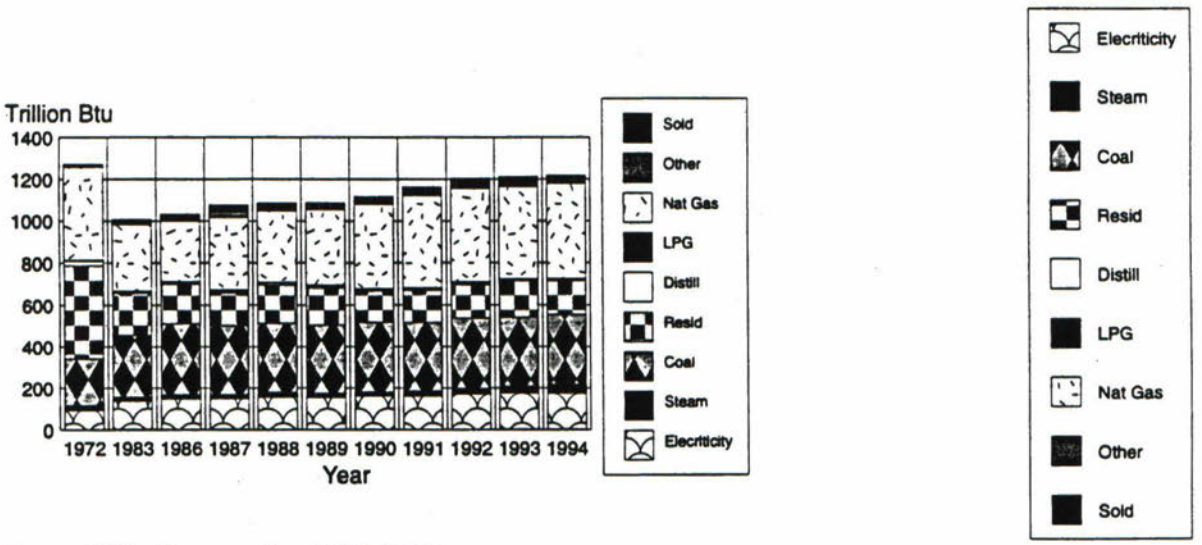
In the very near-term, fuel switching from high-carbon fuels such as coal to lower-carbon fuels such as natural gas is feasible and is already included in most energy forecasting models. In the near and medium time frame, biomass and black liquor gasification technologies described in Section 4.3.3.1 provide the option of switching from a high-carbon to a "no-carbon" fuel. Biomass is considered "no-carbon" because we assume the CO_2 produced will be rapidly resequestered by growing biomass feed stock (see Chapter 7 for more detail on biomass). These technologies can also be considered PSEM technologies because they replace inefficient biomass boilers and grid electricity with biomass gasification cogeneration. Black liquor technology utilizes black liquor gasification instead of improved efficiency recovery boilers (which are the replacements implicit in the modeling calculations of Section 4.2.2). Biomass gasifiers replace inefficient boilers for steam and electricity. These technologies allow the industry to generate more of its own electricity which leads to the offset of purchased electricity. The extra generation of biomass-based electricity is not included in the modeling calculations of Section 4.2.2 and is responsible for the carbon offsets calculated here. Although no examples are provided, other renewable energy-powered industrial technologies (e.g., solar detoxification) could also be considered low-carbon fuel-switching technologies.

4.3.3.1 Integrated Gasification Combined Cycle Technology for the Forest Products Industry

Integrated gasification combined cycle (IGCC) technologies can significantly impact the carbon reductions expected in the forest products industry in two ways: (1) by increasing energy self-generation and (2) by better utilizing residues from the forest management and manufacturing processes. Potential offsets of carbon emissions by 2010 are approximately ten MtC equivalent per year in the high-efficiency/low-carbon scenario. The efficiency scenario could achieve offsets of about 5 MtC equivalent per year. To achieve the carbon reductions in the high-efficiency/low-carbon scenario, it will be necessary to facilitate early commercialization to reduce investment risk and provide an incentive for industry to commit the resources necessary to implement these advanced technologies.

The pulp and paper industry purchases 43% of its energy and uses a diverse mix of resources including electricity, steam, coal, residual and distillate fuel oil, liquid propane gas, and natural gas. In 1972, the industry used oil for nearly a quarter of its purchased energy but this proportion decreased to 6.9% in 1994 by doubling purchased electricity and increasing coal purchases by 50%. This complex purchased fossil fuel and energy pattern is shown in Figure 4.6.

Figure 4.6 Purchased Energy in the U.S. Pulp and Paper Industry by Fuel Type, 1972–1994



Source: Miller Freeman, Inc. (1972–1994)

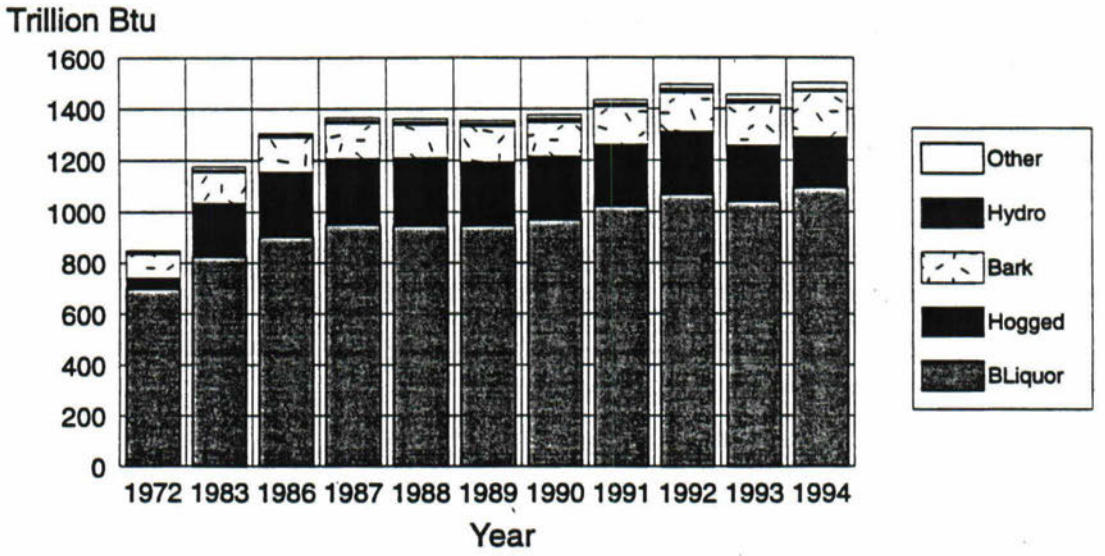
The industry self-generates the remaining 57% of its required energy through the recovery of energy and chemicals in spent black liquor, use of residues such as hog fuel and bark in boilers, and cogeneration of heat and power (see Figure 4.7). The American Forest and Paper Association (AF&PA) estimates that use of these energy sources displaced more than 227 million of barrels of oil in 1994 (Miller Freeman, Inc. 1996).

These fuel switches, increased cogeneration, and energy conservation measures resulted in a decrease in energy intensity. Even though total energy consumption increased over the period 1972–1994, energy consumption per ton of product output decreased by 21% (Miller Freeman, Inc. 1997).

Two opportunities for further improvements were analyzed in detail: increased self-generation from black liquor and increased recovery of usable energy from hog fuels and bark coupled with increased recovery of forest residues and pre-commercial thinnings. Increased self-generation offsets purchases

of electricity and coal, and thus offsets CO_2 emissions.[17] These higher-efficiency processes could also increase the industry's electricity production for return to the grid.

Figure 4.7 Self-Generated Energy in the U.S. Pulp and Paper Industry by Fuel Type, 1972–1994



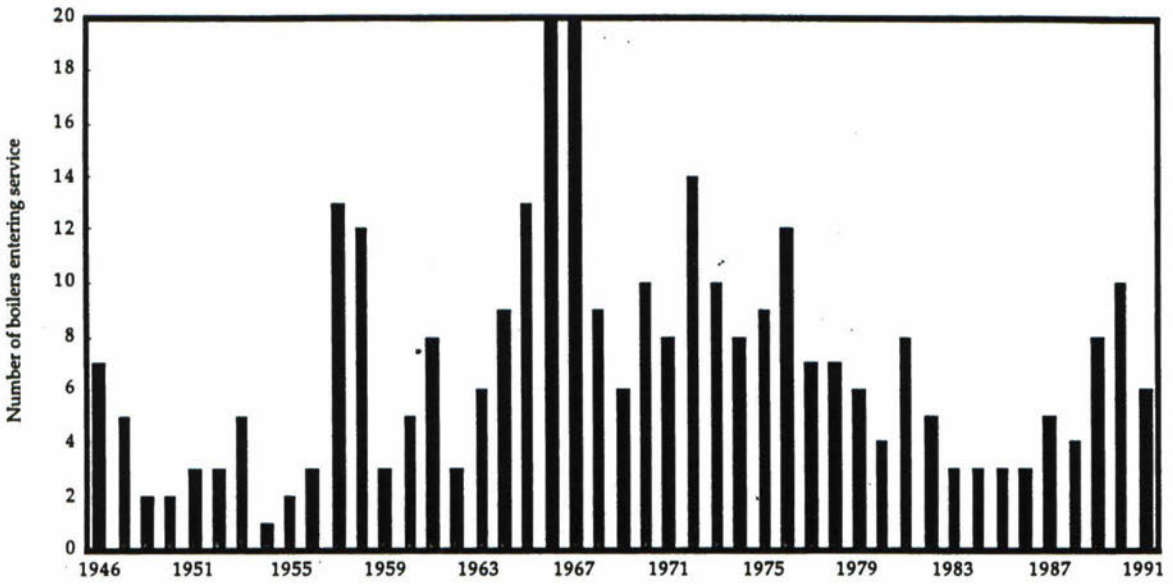
Source: Miller Freeman, Inc. (1972–1994)

Kraft Recovery Boiler Replacements. Traditionally, about 40% of the energy used in a mill is generated from burning the lignin solids. Lignin is the portion of wood that holds the fibers together and makes them stiff. The pulping process separates the lignin from the pulp fiber. The lignin is a dilute solution which is evaporated and burned in a boiler designed to recover the pulping chemicals; heat from combustion is used to make steam. Some of the steam is used to supply the mill's needs and some is used to generate electricity for the mill.

In the black liquor gasification combined cycle process, a little less steam is generated but two to three times more electricity is produced. Process changes designed to make mills more environmentally friendly tend to change the balance of energy forms that a mill uses. Mills are using less steam energy and more electrical energy; the combined cycle process fits right into the future process needs.

The technology is coming on the scene at an opportune time because most of the existing recovery boilers in the industry are reaching the end of their useful safe operating life. The majority of recovery boilers were put into service between 1955 and 1980, with a peak period around 1967 (see Figure 4.8). For environmental and safety reasons the industry is developing alternative technologies in anticipation of replacing these boilers after a 40-year service life. The need for capital replacement creates an opportunity for penetration of new, high-performance, environmentally acceptable technologies. The gasification component of the replacement technology is already at the early stages of commercial deployment, mainly as a means of expanding mill electric generation capacity in situations where the current recovery boiler limits throughput. There is a need for chemicals recovery cycles to be tested and for the integrated cycle to be demonstrated. Expediting RD&D could allow significant carbon emissions offsets by matching the timing of technology development and commercialization to the need for boiler replacement.

Figure 4.8 Kraft Boilers in Service in the United States



Source: American Forest and Paper Association

A major barrier to the adoption of black liquor IGCC systems is the central role that the current recovery boiler plays in the chemical and energy recovery of the mills. Typically, this part of the pulping process has to reliably operate at full throughput with annual capacity factors of greater than 95%. A further barrier is the need for process heat. Increasing the electricity output will require a concomitant improvement in process heat utilization since the steam output of the black liquor IGCC system will be 21% less than that of the recovery boiler, even though the electricity output is effectively doubled.

Replacement of the current recovery boilers by new technology based on gasification to recover both process chemicals and the energy content of the dissolved lignin has the potential to produce 104 TWh of electricity per year, offsetting about 100 Mt of CO_2 emissions. Full replacement of the current recovery boiler capacity at the 1996 production volume would offset 26 MtC equivalent per year. Based on a rate of recovery boiler replacement that assumes a 40-year life for the existing recovery boilers, the 2010 displacement is 5.2 MtC equivalent per year, and the 2020 displacement is 8.7 MtC equivalent per year. The methodology used to determine the replacement rate, on which the projected carbon reductions are based, is discussed in Appendix D-4. The black liquor IGCC system is designed to meet New Source Performance Standards (NSPS), and would also have low NO_x and SO_x emissions. Investment costs for integrated gasification combined cycle are forecast to be less than those for replacement with a conventional recovery boiler system, on a dollar per kilowatt-hour basis. It is anticipated that IGCC systems would be competitive against electricity purchases at $35/MWh.

Residual Biomass Boiler Replacements. Food processing, wood products, and pulp and paper are industries that generate large amounts of residual biomass (e.g., waste wood and bark). While much of this biomass is currently being used, if it were gasified and used to cogenerate steam and electricity, it would substitute for (largely) fossil fuel-produced electricity. Advances in turbine efficiency (see Section 4.3.2.1) make this an economically attractive option. By using residues from pulping processes as well as biomass from forestry operations in conjunction with gasification and combined cycle

technologies, 2.3 GW of capacity can be put in place by 2010, offsetting 4.8 MtC equivalent per year. This would represent about one-third of the potential mill conversions projected to need replacement by that time. Because of the stage of development of the technology and its markets, a conservative estimate would reduce replacements from one-third to one-quarter of the potential mill conversions. Using the more conservative penetration, the carbon replacement potential from gasification of residual biomass is 3.6 MtC equivalent per year.

Approximately 200 mills are already producing heat and some power from the use of residual biomass in their processes.[18] The majority of in-place boiler units entered service between 1965 and 1975 and need replacement; they are either reaching the end of their service lives or they may have difficulty meeting environmental regulations (or both). Residual biomass gasification can penetrate this replacement market with the potential to double the net rate of electricity generation – from a generation efficiency of about 15% to 35%. The technology is already in the early stages of commercialization with the first 18 MW IGCC operating in Sweden. Prototype units are being demonstrated elsewhere in Scandinavia and the United States.

The current cost of this technology is approximately 50% over the plant cost when the technology is mature. Incentives will be necessary to facilitate entry of the technology into the replacement market. One proposal is a capital cost buydown to bring technology costs down.

The gasification system is designed to meet New Source Performance Standards (NSPS) and would have low NO_X and SO_X emissions. Biomass growth and harvesting would be according to best practices, and to some extent the biomass fuel source could include materials that are currently landfilled and thus contribute to landfill methane emissions.

4.3.4 Low Process Carbon Technologies

Low-process carbon technologies reduce or avoid the emission of non-combustion CO_2 and other greenhouse gases in industrial and other processes. As shown in Table 4.13, 92% of the carbon equivalent emissions of process carbon are due to non-CO_2 greenhouse gases that have far higher global warming potentials (GWP) than CO_2.

4.3.4.1 Industrial Sources of Non-CO_2 Greenhouse Gasses

Although non-CO_2 industrial emissions of greenhouse gasses are small by weight, they have GWPs that range from 21 for methane to 23,900 for sulfur hexafloride (SF_6). Figure 4.9 shows the relative contribution of these other gases in MtC equivalent. The largest non-CO_2 greenhouse gas contribution is from methane (CH_4), which is responsible for 177.5 MtC equivalent and has a GWP of 21. Next is nitrous oxide (N_2O) which is responsible for 39.1 MtC equivalent and has a GWP of 310. Finally, in 1994, various halocarbons and other engineered chemicals amounted to 29.5 MtC equivalent. These engineered chemicals are a source of concern since their emissions are growing rapidly – and the United States is the major source. As shown in Table 4.13, emissions of these other greenhouse gases from agriculture (27%), mining/energy extraction (25%), service (24%), and transportation (8%) sectors are important.

The manufacturing sector accounts for 14% of carbon equivalent emissions due to other greenhouse gases. The manufacturing processes that generate GHG emissions include:

- Waste emissions of CF_4, C_2F_6, C_3F_8, NF_3, and CHF_3 from plasma etching, chemical vapor deposition (CVD), and CVD chamber cleaning in semiconductor manufacturing;

- Waste emissions of SF_6 from the manufacture of transformers, circuit breakers/load-shedding devices, and electrical distribution components where SF_6 is used as an insulator;
- By-product emissions of N_2O from adipic acid manufacture;[19]
- Waste methane emissions from production of ethylene and styrene;
- PFC emissions from aluminum production (see Section 4.3.4.3); and
- Waste emissions of SF_6 from magnesium casting in which SF_6 is used as a cover gas to protect against catastrophic oxidation.

Table 4.13 Process Carbon Emissions and Energy Use by Sector

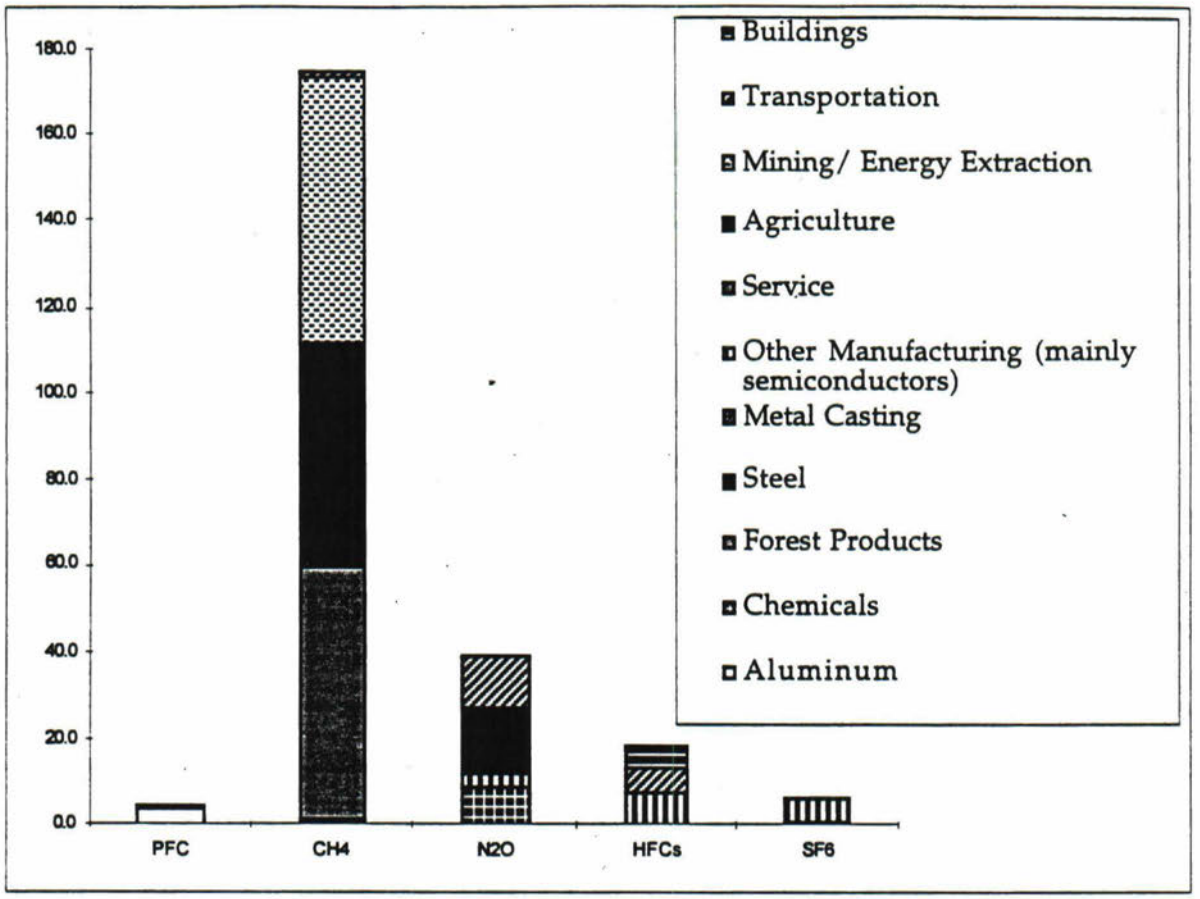
	Carbon Emissions (MtC equivalent)			
	Process CO_2*	Other GHG Carbon Equivalent	Total Carbon	Energy Use (quads)
Manufacturing	18.4	33.0	51.4	22.4
Service	0	58.2	58.2	
Agriculture	0	66.7	66.7	
Mining/Energy Extraction	0.9**	61.5	62.4	
Construction	2.0	0	2.0	
Subtotal Industry	**21.3**	**219.4**	**240.7**	**32.6**
Buildings	0.0	5.3	5.3	33.7
Transportation	0.0	19.0	19.0	25.5
Total	**21.3**	**243.7**	**265.0**	**91.8**

*Source: EIA 1996

**Gas flaring.

While none of the manufacturing emissions are particularly large, we note that global emissions of SF_6 are increasing at a rate of 7–8% per year. This is of particular concern because SF_6 has a very high global warming potential of 23,900 and an expected lifetime of 3,200 years, making it a very potent greenhouse gas. Thus SF_6 emissions alone are increasing at a rate of 0.5 MtC equivalent per year (EIA 1996). Several emerging technologies may be immediately helpful in avoiding these emissions. For example, applications of high temperature superconductor technologies include transformers and current limiters that act as circuit breakers (Platt 1997). Many of these emissions are seen not only in energy-intensive industries but also in "high-tech" manufacturing industries. These non-energy-intensive industries include semiconductor manufacturing and equipment manufacturing for the electric utility industry. Due to scope and time constraints, technology options to reduce these emissions are not addressed in this report but are an important area for future analysis.

Figure 4.9 Non-CO_2 Greenhouse Gas Emissions in the United States (MtC equivalent)



Source: EIA (1996)

4.3.4.2 Process CO_2 Emissions

Compared to other greenhouse gases, process CO_2 emissions are relatively small, accounting for only 9% of process carbon emissions and less than 5% of industrial combustion-related CO_2 emissions. Overall, the industrial sector directly emitted about 23 MtC from CO_2 industrial processes.

The primary industrial processes that generate process carbon emissions include:

- The calcination of limestone in cement manufacture (largest single source);
- The manufacture and consumption of limestone (e.g., in lime kilns, iron smelting, steel making, glass manufacture and flue gas desulfurization);
- Dolomite consumption;
- Soda ash manufacture and consumption (e.g., in glass manufacture, flue gas desulfurization, and chemicals production);
- CO_2 manufacture;

- Gas flaring; and
- Aluminum production.

There has also been a disproportionate increase in process CO_2 emissions relative to combustion-related CO_2 emissions. Over the past eight years, process CO_2 emissions have increased nearly 16% while combustion-related CO_2 emissions have increased only 4%. However, these process carbon data are highly uncertain due to their variability across sites due to non-uniform measurement technique. For example, the carbon emissions could be flat in reality but appearing to rise because measurements are more comprehensive today.

The following sections describe carbon savings in the aluminum and cement industries that are possible given aggressive RD&D and commercialization strategies.

4.3.4.3 Low-Carbon Technologies in Primary Aluminum Production

Because of the very high chemical stability of aluminum oxide and other aluminum compounds, the production of aluminum metal was not feasible until the nineteenth century when electrical power generation facilities became available to permit commercial electrolytic reduction operations. Creation of today's world-wide aluminum industry occurred after the simultaneous inventions by Hall and Heroult of a process for high-temperature reduction of aluminum oxide dissolved in a molten fluoride salt using a carbon anode which is consumed during the process reacting to form carbon dioxide.

The global warming potential associated with aluminum production results from several factors

- First, carbon dioxide is generated at fossil fuel plants that produce the electricity required for the electrolysis process.[20] State-of-the-art Hall-Heroult cells achieve power consumption levels as low as 13,200 kWh/tonne of aluminum produced; however, most aluminum plants require more electricity per tonne of product.
- Second, the production of one metric ton (or tonne) of aluminum leads to the generation of at least 1.22 tonnes of process carbon dioxide (or 0.33 tonnes of carbon) from the reduction cell operation.
- Third, global warming effects also result from the generation of perfluorocarbons (CF_4 and C_2F_6) during instabilities in the cell operation (called "anode effects") that occur when oxide concentration in the cell bath becomes undesirably low. In 1994, aluminum smelting is estimated to have emitted the equivalent of 4.2 million metric tons of carbon equivalent, from perfluorocarbon (PFC) byproducts (EIA 1996).

Further reductions in the levels of greenhouse gas emissions associated with primary aluminum production will require:

1. Development of reduction technologies that require less energy for primary metal production;
2. The development of inert, non-carbonaceous anodes that are not consumed through the reduction process; and
3. The development of improved cell designs and operating control strategies to reduce PFC emissions.

On the basis of ongoing research on aluminum reduction technology, the desired improvements will require the development and commercialization of retrofit advanced cell technology with wettable cathode and inert anode components. Two scenarios have been developed: an efficiency scenario, based on the development and use of wettable cathodes with conventional carbon anodes, and a high-efficiency/low-carbon scenario, based on the addition of inert anodes to the advanced cell.

Under both the efficiency and high-efficiency/low-carbon scenarios, R&D on advanced aluminum production cells would be funded by both the federal government and the private sector. However, under the high-efficiency/low-carbon scenario, the development of inert anodes and the associated control systems would be pursued more aggressively. In either case, alternative cathode and anode materials, advanced cell designs, and advanced operating control methods would be developed with the overall goal of reducing the cell voltage (electrical energy requirements and associated power plant CO_2 emissions), eliminating CO_2 cell emissions, and significantly reducing emissions of PFCs arising from cell operating instabilities. In the discussion below, we analyze the incremental energy efficiency improvements and reduced carbon gas emission savings from these advanced low-carbon technologies for primary aluminum production.

Under the efficiency scenario, the wettable cathode part of the advanced cell is forecast to be ready for commercial operations by approximately 2005. Conventional, non-wettable cathode cells operate with thick metal layers above the cathode surface. In contrast, use of wettable cathodes permits cell designs in which product metal can be drained from the cathode to collection sites within the cell leaving only a thin film of metal at the cathode surface. Normal undulations at the metal surface resulting from electromagnetic stirring and gas bubble driven circulation are virtually eliminated with wettable cathodes permitting cell operations with reduced anode-cathode spacings. In combination with advanced process sensors and control systems to optimize cell operation, the potential energy savings are estimated to be as high as 15–20% over conventional cells (DOE 1990). These same sensors and control systems would yield reduced levels of PFC gas emissions. These technologies will be designed for simultaneous or independent retrofit use on existing cells.

The high-efficiency/low-carbon scenario forecasts the additional development of inert anodes. The most promising materials presently being evaluated are ceramic/metal composites consisting primarily of nickel oxide and nickel ferrite with a copper/nickel metal phase (Windisch and Strachan 1991). These permanent anodes would also eliminate CO_2 emissions associated with the manufacture and consumption of carbon anodes. If successful, the advanced cell would result in an approximate 27% reduction in the electricity requirements for primary aluminum production.

Research would be scheduled so that commercial-scale demonstration tests (individual commercial sized reduction cells up to the actual conversion of an operating potline) would be in operation by approximately 2005. To re-engineer an existing smelter site with radically different production may require a capital investment ranging from $500,000 to $2 billion. For investments of this scale, conclusive demonstrations defining operating performance, operating costs, and equipment lives must be completed to achieve industry acceptance and widespread adoption.

The economic feasibility of the advanced technology would be enhanced if federal policies promoting further reductions in carbon emissions were established. Even without such policies, the U.S. aluminum industry has expressed a goal of eliminating process CO_2 emissions in primary aluminum (Energetics 1997). Furthermore, trends toward increased use of aluminum in the transportation sector to improve vehicle fuel efficiency through weight reduction could significantly increase demand for primary aluminum, further increasing the economic feasibility of the advanced cell technology.

Under the efficiency scenario, we assume that five of the existing 22 aluminum plants operating in the U.S. (American Metal Market 1997) are retrofitted to use the advanced wettable cathode cell. With an average plant capacity of 190,000 tonnes of aluminum per year and an average annual electricity consumption of 13,200 kWh per tonne of aluminum, electricity efficiency improvements of 17% in these five plants would result in 0.19 million tonnes of reduced carbon-equivalent emissions in 2010.[21] This is 0.09 MtC more than the efficiency scenario described in Section 4.2.2.[22] In addition, the PFC emissions from anode effects are projected to be halved in those five plants where wettable cathodes are installed. This would represent an 11.4% (or 0.48 MtC) reduction in the aluminum industry's carbon equivalent emissions of 4.2 MtC.[23]

Under the high-efficiency/low-carbon scenario, use of the advanced, inert anode by 10 of 22 plants could lead to reduced carbon emissions by 1.6 MtC equivalent, of which 1.00 metric tonnes of carbon savings are due to the reduced consumption of electricity.[24] This is equivalent to 0.67 MtC over the high-efficiency/low-carbon scenario described in Section 4.2.2.[25] An additional 0.6 Mt of carbon savings result from the elimination of carbon emissions from the production cell.[26] The use of inert anodes to eliminate the process CO_2 emissions from smelting was not considered in Section 4.2.2; thus, all of these carbon reductions are accounted for here. In addition, the PFC emissions from anode effects are projected to be eliminated in those 10 plants where inert anodes are installed. This would represent a 45.5% (or 1.91 MtC) reduction in the aluminum industry's carbon equivalent emissions of 4.2 MtC.[27]

These carbon reduction estimates are summarized in Table 4.14. The advanced aluminum production cell in the efficiency scenario accounts for 0.6 MtC (or 0.5 to 1.0 MtC) of reductions above the carbon reductions already incorporated in Section 4.2.2. The high-efficiency/low-carbon scenario accounts for 3.2 MtC (or 3 to 3.5 MtC) more than the carbon reductions already incorporated in Section 4.2.2. Technical details of the advanced aluminum production cell are discussed in Appendix D-6.

Table 4.14 Carbon Reductions from Advanced Aluminum Production Cells, in 2010 (MtC)

Sources of Carbon Reductions	Efficiency Scenario	High-Efficiency/Low-Carbon Scenario
Electricity Savings		
•Included in Section 4.2.2	0.1	0.3
•Increment above Section 4.2.2	0.1	0.7
Cell Production	0	0.6
Reduced Perfluorocarbons	0.5	1.9
Total	**0.7**	**3.5**

4.3.4.4 Replacing Cement Clinker with Solid Wastes

The cement industry is the single largest source of U.S. process CO_2 emissions and a major energy user. The annual process CO_2 emissions from the U.S. cement industry are 9–10 MtC equivalent (EIA 1996). Energy-related CO_2 emissions are of similar magnitude depending upon the cement kiln technology. Some estimates indicate that each ton of cement clinker produced results in the direct emission of one ton of CO_2. Other estimates with different kiln technologies have a much higher energy/process CO_2 ratio. Of the process emissions, about 60% of the direct emissions are from calcination of limestone and the other 40% are from combustion products from fossil fuels that directly or indirectly supply the energy for calcination.

Nearly all cement in the United States is made from ground clinker intermixed with gypsum. One technically straightforward and cost-saving way to reduce energy input and carbon emissions per ton of cement is to replace some of the clinker with abundant utility and steel plant wastes such as fly ash or granulated blast-furnace slag. Such a replacement makes cement with somewhat different properties, but still a satisfactory building material. Most European countries allow such cements and have found that these cements last longer and are more tolerant to salt water than pure clinker cement. However, U.S. product specifications (Standard Specification for Portland Cement, ASTM C150) do not allow any extra ingredients in cements. These specifications are difficult to change because the small minority of those who might lose markets (e.g., non-integrated cement producers) can easily stop changes under the current system. A recent study (Sauer 1997) estimates that changing the U.S. specifications to permit inter grinding could reduce both energy and process CO_2 emissions by 5–20% per year by reducing demand. If the specifications were changed, it is likely the new technology could be rapidly adopted by U.S. cement manufacturers, especially the multi-national firms that are already using this type of cement in Europe. Under the high-efficiency/low-carbon scenario, the barriers to this technology could be overcome. In addition, there would be motivation to conduct further research, development and demonstration activities exploring a wide range of cement inter grinding materials and percentages and to ensure that they provide the same or improved performance. Based on these studies and assuming a low-carbon, aggressive R&D scenario, our estimate is that by 2010, 1–2 MtC equivalent of industrial carbon emissions could be avoided due to cement inter grinding and replacement.[28]

Though the manufacturing process has remained the same, the U.S. cement industry has changed over the past 20 years. The number of kilns in operation has dropped by 50% since 1975. There has been a 28.3% improvement in fuel efficiency since 1975, dropping the energy required per metric ton of cement from an average of 7.26 MMBtu in 1975 to 5.20 MMBtu in 1994. Over 60% of U.S. clinker capacity is foreign owned or affiliated with foreign firms, and most of these are integrated European cement companies. The primary customer, accounting for 60% of shipments, is the ready-mix concrete industry which supplies concrete, mixed to customer specifications, to construction sites (Bureau of Mines 1994). Concrete typically contains 10–15% cement as a binder. Cement demand is projected to grow at 1% per year, half the rate of GDP.

On average, energy accounts for between 30 and 40% of cement manufacturing cost. Electricity represents about 10% of energy input, but frequently accounts for close to 50% of total energy cost. Integrated cement producers and ready-mix concrete suppliers would benefit from replacing high cost clinker with low- or negative-cost materials. The cement industry is already a leader in waste utilization. More than half of plants responding to a 1994 survey reported the use of one or more types of waste as fuel. This technology could, however, speed the decline of non-integrated cement producers.

In addition to reducing CO_2 emissions, this technique also reduces NOx, SO_2, and particulate emissions associated with electricity use. It also reduces solid waste by replacing quarried raw materials with wastes and by-products such as fly ash, foundry sands, and mine tailings.

4.4 PROVEN INDUSTRIAL TECHNOLOGIES

Although our forecasting methodology does not draw directly from detailed representation of individual technologies, the forecast savings that are expected in each sector will be drawn from a variety of sources of new technologies and business practices. This section illustrates the range of commercially available and near commercial innovations that firms in these industries can draw upon to achieve the additional reductions in energy use that are considered feasible in the HE/LC case and

could contribute to this projected decline. In addition, we provide examples of technologies that directly displace carbon in Section 4.3.

We provide illustrative examples of currently-available technologies that we believe could be integrated into industry to provide the savings suggested by the model simulations for each energy-intensive industry; we also provide examples of cross-cutting technologies. We describe how each technology is used and from what type of efficiency it draws its energy and cost savings.

Some technologies recover or reduce the production of waste heat in high-temperature applications while others optimize the process load to the energy-using equipment. Many of the most successful technologies have multiple benefits, including pollution prevention or productivity-enhancing features. A technology that reduces product loss or increases process throughput will often reduce labor or material costs as well as energy costs. For example, continuous casting, widely adopted by the steel industry, is cost-effective based on its energy savings alone but industry has adopted continuous casters in large measure because of the improvement in steel quality and because it reduces losses. Similarly, impulse drying, an emerging technology, saves energy, but also allows additional throughput on the paper-making machines and will improve the quality of the product.

While it is felt that these technologies are representative and have the potential to be readily accepted by industry, the estimates of energy savings provided below *do not represent any industry consensus* of the relative difference between the new technology and average practice. Instead we rely on available, published literature that assesses the performance of these technologies and business practices.

The diversity of industries, businesses, plants, and processes implies that not all of these examples will be universally cost-effective, or even applicable. Site- or plant-specific constraints may prevent the use or economic acceptability of a technology for retrofit applications that would be readily accepted in a new plant design. In many of the most energy-intensive process industries, few green-field plants are being built in this country, further limiting some applications. While we do not consider explicitly the economics of *when* to replace old equipment, we understand that a variety of considerations enter into this business decision, including:

- How learning curves tend to continually lower the costs (including energy costs) as cumulative production experience with new technology is gained;
- Countervailing factors like "wear and tear" that tend to increase costs over time;
- How the introduction of new equipment can alter the economics of existing equipment; and
- Available design trade-offs between capital and other costs, especially energy costs.

New and replacement capacity will be put into place at many existing plants based on these and other decision variables. The opportunity for new technology to be adopted occurs at the point in time when these decisions are made. It is at this point that energy prices and capital discount rates can influence the decision to purchase new technology and thus the adoption of technologies for which examples are given below.

Many of these technology examples exhibit energy savings of more than 5-10% relative to current average practice, but the turnover rates of the capital stock in the energy- and capital-intensive industries require our projections to take this into account. In 13 years, many of these technologies (and many others not listed here) are capable of reaching higher levels of penetration, but most will not achieve 100% penetration. In addition, the technology examples often account for some fraction of

the energy use in that sector. However, the examples show that there are many ways in which efficiency in industry can be increased, given the right incentives.

Brief descriptions of energy-efficient technology opportunities for the industrial sector are provided in the following sections; more details are available in the associated appendices and references.

4.4.1 Cross-Cutting Technologies

There are a variety of cross-cutting technologies that are not process- or product-specific in operation in industry. Some include lighting and heating, ventilation, and cooling technologies that are also commercial applications and are not discussed here (see Chapter 3). Others include sensors and computer control systems which have a common underlying technology, but have a variety of configurations and benefits depending on the industry. There are two major ways that all of industry can benefit from improved efficiency: cogeneration and improved motor systems.

4.4.1.1 Combined Heat and Power

Combined heat and power (CHP) is the joint production of useful steam and electricity, either for on-site use or sale back to the electric grid. There are substantial thermodynamic advantages to the joint production of heat and power that could greatly reduce generation losses from traditional power production and would reduce carbon emissions system-wide. The advantage of such an approach is that little additional fuel is required for the electricity generation over that required for simple steam production. Thus, the efficiency for use of the thermal energy available from the fuel is higher than with separate electricity generation and steam production, and the net greenhouse gas emissions can be reduced by the application of cogeneration. Based on a typical boiler configuration, the gas turbine with heat recovery steam generation is typically the most cost-effective (Boyd et al. 1996). CHP can also help reduce carbon through fuel switching to low- or no-carbon fuel. Under the BAU case, CHP power production will grow to 333 TWh by 2010. See Section 4.3.2 for an example of a CHP system that can reduce carbon emissions far more than predicted in the BAU.

4.4.1.2 Motor Systems

Energy-efficiency opportunities associated with electric motor drives derive not so much from the replacement of motors with high-efficiency motors as from energy-conscious design throughout the system employing the motor drive. Such a systems approach (see Section 4.3.2) has also resulted in significant non-energy savings when motor systems are improved.[29] The system includes power supply lines, controls, motor feed cables, the electric motor, the drive and transmission system, and the driven load. Each of these system elements may present a significant opportunity to conserve energy.

The power supply and control systems affect efficiency in three ways. First, power is consumed by resistance losses in the supply wires. Second, losses in the supply wires may contribute to voltage imbalance in the power supplied to a polyphase motor, leading to reduced efficiency and possible motor damage. Third, other system loads and certain control devices, particularly adjustable speed drives, can distort the sinusoidal AC voltage provided to the motor, resulting in efficiency and torque losses, vibration, and possible bearing damage, which is accompanied by increased friction.

Losses associated directly with the electric motor include electrical resistance losses, magnetic losses, friction and air flow losses, and stray losses associated with manufacturing quality limitations. High-efficiency motors address these losses, though efficiency improvement over standard motors may only average 5% to 7%. While an electric motor consumes less than full power when the load it serves is less than the motor rating, the efficiency of the motor declines dramatically as the load declines below

40% of rated load. Since motor over sizing is common practice, this provides a significant efficiency improvement opportunity.

Losses associated with drive systems are frictional losses in belt and gear systems. Higher losses are associated with greater speed reductions, which may improve the relative economics of adjustable speed drives (motor speed control). While drive transmission efficiency may be well over 90%, it may be below 50% as well. Thus, drive system design may offer more savings opportunity than motor replacement.

The most important savings opportunities will often lie in specification and design of the driven load. In the extreme, process changes may eliminate the need for the load entirely or equipment substitution can reduce power requirements. For instance, mechanical conveyors may be used rather than pneumatic conveyors at a substantial energy savings. More commonly, proper selection of loads such as fans, pumps, and compressors to match the intended application requirements will result in the equipment operating at higher efficiency and presenting less load to the electric motor. Then, proper matching of the remaining load to a motor, perhaps with variable speed control, will result in optimal overall system efficiency.

4.4.2 Pulp and Paper

Paper manufacturing was one of the most energy-intensive industries in the United States in 1994, using more than 18,500 Btu per dollar value of shipments. The manufacturing of paper requires that a fiber source, normally wood, be chipped, digested, bleached, and then formed as a slurry from which paper or board is made. Once formed as paper, the product must be dried. Large amounts of steam and power are used to debark and chip the wood, digest the wood, bleach the pulp, and dry the paper products. Much of this energy source (over 50%) comes from the reprocessing of lignins from the wood, bark, and unusable portions of the tree. In lumber and wood products, the fraction of biomass energy sources is nearly 70%.

In paper manufacturing, any technology that will economize the use of steam, reduce the need for heat, better utilize the biomass fuel sources available, or help to balance both steam and power needs will improve the performance of the industry. The technologies that hold promise to reduce energy and carbon emissions in the near-term continue to economize on the use of heat. Longer-term options alter the balance between steam and power. The most promising near-term options are discussed below.

Impulse Drying: Impulse drying reduces the huge energy requirements of evaporative drying by removing more water in the pressing section and reducing the amount of water which must be evaporated. The total energy savings for full implementation of this technology are estimated to be approximately 0.25 quad/yr. Without an invigorated effort, the net energy savings are estimated to be about 12 trillion Btu annually from a market penetration of only 65 drying units by 2020. Impulse drying methods allow papermaking machines to run at higher speeds, thereby increasing production rates. This drying method reduces energy use by one-third, reduces production costs by $5 per ton of paper, improves paper strength by 25%, increases productivity by as much as 80%, and reduces carbon dioxide emissions as well.

Multiport Cylinder Drying: The evaporative drying in a paper mill is accomplished by winding the continuous sheet of paper serpentine over a series of rollers. The rollers are pressurized with steam which condenses on the inside of the roller. The multiport cylinder drying concept uses an alternative method to remove the condensate from the drier, which reduces the condensate film thickness inside the drier to 25-30% of conventional technology. This improves heat transfer and increases drying.

On-Machine Sensors for Paper Properties: The development of new sensors to provide real-time feedback on whether the process and product are within specification can save the energy of reprocessing off-grade material and allow the use of greater amounts of recycled fiber. With an on-line sensor for strength properties the process variability can be reduced and greater proportions of recycled fiber utilized. A 10% reduction in refiner energy at a single mill saves more than 70 billion Btu/year. Reducing the normal off-grade production rate by 50% (from a typical 5% to 2.5%) can save an additional 118 billion Btu/year. If 300 plants adopted these sensors, the annual savings would be about 60 trillion Btu.

Biomass Gasification Cogeneration: The pulp and paper industry is about 57% energy self-sufficient, due to the use of wood residues (i.e., hog fuel and bark, pulping wastes, and cogenerated electricity). The gasification of biomass and electricity generation through a combined cycle would increase the electricity output of the paper industry, further reducing purchased electricity needs. To meet the in-plant process steam requirements, this biomass-based integrated gasification and combined cycle (BM-IGCC), would require an increased utilization of wood residues (about double) possibly from wastes in plantation forestry or other sources. If one-third of the current population of hog and bark boilers were to be replaced with BM-IGCC, many of which will be retired by 2010, then cogeneration output from the paper industry would increase by 17 billion kWh, about 27% compared to 1994 levels. This would reduce total U.S. industrial electricity purchases by 1.3% in 2010 and carbon emissions by about 1.3 million metric tons.

4.4.3 Chemicals

The chemical industry is almost too complex to characterize as a single industry. Some products – chlorine and other industrial gases – are made electrolytically or using electricity to compress and liquefy gases. Other processes, such as petrochemical processing, require high temperatures and pressures to effect the chemical combination or separation that is required. Within chemical manufacturing there are over 30 industries and more than 10,000 products. A recent study by Steinmeyer (1997) found that, in the chemicals industry, simple capital-energy tradeoffs (e.g., using larger pipes and heat exchangers) result in a 37% reduction in process energy consumption for a cost of less than 1.5% of total production costs; this study examined only energy-related costs. Another recent study by Elliot (1997) showed that productivity savings are often far larger than energy savings. For example, at the Louisiana Division of Dow Chemicals from 1982 to 1993, the average total annual savings from efficiency projects was 3.2 times the energy savings (Nelson 1993).

Reaction and separation are at the heart of most chemical engineering processes, and they typically require heat, high pressure, or both. Because of these requirements, the industry in 1994 used 5.3 quads of energy (second only to Petroleum Refining) and required nearly 16,000 Btu per dollar of product shipped. Promising technologies for the near-term are those that economize on the use of heat or cooling or bring the two in better balance. Examples are:

Pinch Analytical Techniques: The "pinch" technique was originally a method for optimizing heat recovery in thermal processes and has more recently been applied as a general optimization tool. Energy savings occur because of the heat recovery process (waste heat from one process is used to provide needed heat to another). In the classic case of heat exchanger networks, the pinch point helps to define the best match between available and needed heat, allowing the heat exchange system to be optimally sized for greatest cost-effectiveness. In early applications, energy savings averaged 30%, with capital cost savings in new plant designs, and one year paybacks in retrofits are common. Refinements to the technique have resulted in typical savings of 50% in new plants and retrofit paybacks of six months. By the mid-1980s the use of pinch analysis was widespread in the chemical industry, and its use has broadened further since then (WEC 1995).

Advanced Distillation Control Techniques: Distillation in refining and chemical industries consumes 3% of total U.S. energy use, which amounts to approximately 2.4 quads of energy annually. In addition, distillation columns usually determine the quality of final products and many times determine the maximum production rates. Distillation columns commonly use 30% to 50% more energy than is necessary to meet the product specifications. It has been estimated that an overall average 15% reduction of distillation energy consumption can be attained if better column controls are applied.

4.4.4 Petroleum Refining

The most energy-intensive processes are: distillation; catalytic hydrocracking, reforming and hydrotreating; alkylation; and hydrogen production. Efficiency improvements can be achieved in the following ways: (1) introduction of more efficient equipment; (2) reducing process activation energies (through improved catalysts); (3) improving equipment integration to recover more heat; and/or (4) adopting improved process control.

4.4.4.1 Monitoring Overall Energy Performance

Refineries could promote energy efficiency by rigorously pursuing a program to monitor equipment/process/overall refinery energy performance to identify when a system or piece of equipment begins to become inefficient so that corrective actions can be initiated.

4.4.4.2 Utility System Improvements

The principal utility systems in a refinery are the cooling, steam power, and fuel-gas systems; they are integrated with virtually every process subsystem. While their impact on the overall refinery operating profit margin is relatively small, the potential for energy savings is substantial (see appendix for details).

4.4.4.3 Process/Equipment Modifications

Major opportunities to reduce energy usage also exist through retrofitting and/or replacement of existing equipment nearing the end of its useful life. Examples of such opportunities are as follows:

Fired (Process) Heaters. Over 60% of the energy used in refineries is obtained from burning gaseous fuels in refinery heaters. For higher temperature processes such as steam reforming, the application of advanced oxy-fuel combustion systems such as Dilute Oxygen Combustion can result in net fuel savings of 25%. These gains can be enhanced further by converting natural gas to hydrogen and carbon monoxide, making use of waste heat generated by the Dilute Oxygen Combustion System.

Boilers. About 20% of all energy used by petroleum refiners is used for generation of steam. One route for improving boiler efficiency is through improved sensors and controls. For example, balancing the burners in a multi-burner boiler and reducing excess air can cut fuel use by 10 to 25%. In single-burner boilers, controlling excess air can lead to similar gains. The technology to automate excess air firing is available, but a practical system remains several years away.

4.4.4.4 Fluid Catalytic Cracking

Fluid catalytic cracking (FCC) is currently the most energy-efficient and widely used of the cracking processes. Improved computer simulations of cracking kinetics should result in an improved commercial technology by the year 2008. Introduction of improved catalysts and other process

modifications would occur somewhat later. FCC improvements could eventually lead to CO_2 reductions of up to 8 MtC.

4.4.4.5 Fouling Mitigation in Heat Exchangers

Seven percent of the total energy consumed in petroleum refining is due to extra energy needed to run heat exchangers that have a fouling build-up. Research indicates that improved operations and retrofits can reduce fouling. An accelerated program of heat exchanger retrofits and better understanding of fouling conditions could reduce CO_2 emissions by 0.5 MtC by 2010.

4.4.5 Glass

The glass industry is comprised of several major product segments, each with their own processes for producing final products. The segments include container, flat glass, wool and textile fiber, specialty, lighting, and hand glass. The major common energy-intensive stage of the glass industry is the glass furnace. There are nearly 500 furnaces in over 200 plants in the glass industry (ignoring the smaller hand glass segment). While there are other stages of product finishing which also require significant amounts of energy, the examples below focus on the glass furnace as the primary area of concern for energy efficiency. Other process and product specific areas of energy efficiency are also possible.

4.4.5.1 Oxy-Fuel Process

Since 1991, the fiber, container, and specialty glass industries have accepted the oxy-fuel process as an alternative to regenerative and recuperative air-fuel furnaces. According to one source, more than 50 major furnaces (20 ton/day) have been converted to oxy-fuel combustion technology (Geiger 1996). In the oxy-fuel process, oxygen or oxygen-enriched air is used in combustion in the melting furnace. It is reported that fuel savings from oxy-fuel conversions are typically 10-15% for well designed soda-lime regenerative furnaces, and at least 30-40% for direct fired or regenerative boro-silicate or lead glasses (Ross 1996). Currently, approximately 15% of the large commercial furnaces in the U.S. have been converted to the oxy-fuel process (Ross 1996).

Oxy-fuel technology also increases furnace productivity by 25%, reduces defects, and eliminates the need for heat recovery (DOE/OIT Impacts, December 1996). There is also a waste-heat-driven thermal swing absorption (TSA) process for producing low-cost oxygen for this process. The TSA system can be used in both the glass and steel industries. This low-cost absorption system selectively absorbs oxygen from air at a cost 30% lower than the best conventional system. This new technology increases productivity dramatically, reduces fuel use by 60%, nitrogen oxides (NO_x) emissions by 50%, and particulate emissions by 30%. The system also eliminates the need for other more costly add-on NO_x and particulate control equipment to meet increasingly stringent environmental regulations for glass and metal melting. The expected energy savings are 28 trillion Btus ($70 million) annually.

4.4.5.2 Advanced Burner Technology

Adoption of newly developed burners in the oxy-fuel process further improves the energy efficiency of the process. Some recent burner designs have shown as much as a 30% decrease in fuel use, as well as improvement of product quality.

4.4.5.3 Glass Batch/Cullet Preheater Technology

The dual batch/cullet preheater uses the oxy-gas furnace's waste heat to preheat cullet and batch before feeding it to the furnace. Preheating cullet and batch reduces the amount of energy and oxygen required in the overall melting process (*GRID* 1996).

4.4.6 Aluminum

Aluminum smelting is highly capital-intensive, with capacity cost estimates ranging from $3,000 per metric ton for expansion of existing facilities to $5,000 per metric ton for new facilities (DOI 1993). Low energy costs in countries such as Brazil, Canada, and Australia have made the international aluminum industry extremely competitive, and near-term construction of smelting capacity is not expected in the United States. Investment in state-of-the-art technology has also been limited by capital constraints. A variety of technologies exist, however, that have the potential to incrementally reduce energy intensity in the aluminum industry in the time frame to 2010.

4.4.6.1 Improving Hall-Heroult Cell Efficiency

The current U.S. composite baseline energy intensity for aluminum smelting is estimated at 15.2 kWh/kg of aluminum, with the potential near-term reduction using retrofit technology estimated at 13 kWh/kg (Energetics 1997). Performance in the range of 13 to 15 kWh/kg has been achieved in domestic smelters through a variety of techniques including enhanced potline controls, better anode rod connections, improved cathode block materials, and increases in anode size resulting in lower current density (Newsted et al. 1992, Jeltsch and Franklin 1992). Additional research to design dimensionally stable cells and to optimize materials use for internal control of cells, and to use signal analysis to analyze cell voltages in potlines, are seen as areas which can improve smelting performance in the next ten years (Energetics 1997). The primary barriers to adoption of high-efficiency technologies may be economic.

4.4.6.2 Materials Recycling

Remelting aluminum scrap requires only a small fraction of the energy required to smelt aluminum from alumina. Remelting is also far less capital-intensive than smelting, which reduces barriers to modernizing. In 1995, aluminum recovered from old scrap was equivalent to about 35% of apparent consumption in the U.S. (DOI 1994). While some of the barriers to higher recycling rates are institutional (e.g., perceived value of recycling beverage containers), technological barriers also exist for some products like aluminum in cars. These include problems with scrap sorting, separation, cleaning, and pre-treatment, which inhibit the increased use of different types of scrap and also contribute to problems with metal quality. Byproduct recycling (e.g., salt cake and spent potlining) is also inhibited by a lack of knowledge of byproduct characteristics. A critical review of the U.S. recycling industry infrastructure could identify ways to enhance aluminum recycling rates (Energetics 1997). Given the magnitude of energy savings associated with recycled aluminum versus virgin aluminum, enhanced recycling may offer the greatest energy savings and greenhouse gas emissions reduction opportunities in the short term.

4.4.6.3 Improve Furnace Efficiency

Improving energy efficiency of melting and holding furnaces offers potential for energy savings in the secondary aluminum industry. Several commercially available technologies exist for reducing energy use in furnaces, including heat recuperators and regenerators and the use of oxygen-assisted combustion. Heat recuperators operate by passing the combustion products through heat exchanger tubes, thus allowing the preheating of inlet combustion air and recovery of heat that would otherwise be exhausted to the atmosphere. Heat regenerators accomplish heat recovery through a paired burner/exhaust system in which the burners alternate in the firing mode in cycles lasting about 20 seconds. Oxygen-assisted combustion uses oxygen in a dual-firing burner to increase furnace melt rates, reduce energy use, and reduce emissions. Energy savings from oxygen-assisted combustion can be substantial (Heffron et al. 1993).

4.4.7 Iron and Steel

Iron and steel industry comprises the ore-based integrated steel plants, the dominantly scrap-based "mini-mills," and specialty steel mills. Steel production via integrated plants has been decreasing, while that of the electric arc furnace (EAF) based mini-mills has been increasing. At present, the production capacity of the mini-mills is comparable to some of the smaller integrated plants. Mini-mills are more energy-efficient, since they use scrap or directly-reduced iron or hot-briquetted iron. If the mini-mill relies mainly on scrap, the range of products that can be produced is somewhat limited by scrap quality issues.

4.4.7.1 Direct Smelting / Direct Reduction

The ongoing process development activities in iron making in the U.S. and abroad clearly indicate a need to minimize coke consumption and increase the use of natural gas and/or coal as a reductant for making solid and/or liquid iron. Energy savings from such technologies arise from by-passing the coke-making stage and frequently from very high throughput. For example, Kobe Steel and Midrex Direct Reduction Corp. have developed a production approach for molten iron that reduces the process from hours to minutes (Metals Industry 1996). Because the product is in molten form, there are savings in downstream steel making operations and the material can be cooled to iron shot or ingots without reoxidation.

This technology eliminates the production of coke and reduces the need for ore preparation by integrating three steel processes into one. Coke-making and ore preparation are responsible for the largest portion of emissions in primary steelmaking. This technology reduces energy consumption by 20-30% and capital costs by 25-50% compared to conventional blast furnace technology. The first commercial applications of this technology are operating in Europe.

4.4.7.2 Scrap Preheating

Energy consumption in EAF operations can be reduced by preheating scrap to approximately 400°C with EAF offgases. Heated metal charges comprising 20-30% of inputs can result in power consumption rates of less than 300 kWh/tonne of liquid steel (Scheidig 1995). The potential energy savings is roughly 90 kWh/ton of liquid steel. For a DC Fuchs shaft furnace, compared to a conventional DC furnace, energy savings of 13.5% and reduced electrode consumption of 29% are estimated. Baghouse dust reduction is estimated at 30% (Haissig 1994). In the dual shaft furnace design, iron particles in the offgas tend to adhere to the scrap, resulting in iron recovery in the melt and leaving the offgas zinc-enriched (Burgmann and Pelts 1995). If zinc levels are enriched to above 25%, the dust may be an acceptable input to zinc refining, rather than requiring disposal as a RCRA-listed hazardous waste (Center for Metals Production 1987). Preheating also reduces furnace tap-to-tap time (normally about an hour) by 12 to 15 minutes (Scheidig 1995), resulting in increased raw steel production capacity, measured in terms of sustainable annual production.

4.4.7.3 Hot Connection

Depending on plant layout, moving forms from the continuous casting operation to the rolling operation with minimal cooling may provide energy savings. Reheat furnaces are generally employed to bring the cast forms back to rolling temperature. Adjusting plant layout to move the cast semi to the rolling operation at a temperature of 600° to 800°C can result in an energy savings of 0.4 to 0.6 GJ/tonne of semi based on the IISI reference plant defined in 1982 (Etienne and Irving 1985). A Dutch study based on a transport or connection temperature of 700°C estimated an 18% reduction in energy for reheating, for a savings of 0.3 GJ/tonne of crude steel (De Beer et al. 1994).

4.4.7.4 Near Net Shape Casting

Near net shape casting provides an example of an innovative and energy-efficient technology that has experienced rapid penetration in a capital- and energy-intensive industry. It is the direct casting of the metal into (or near to) the final shape (e.g., strips or sections), replacing the present energy- and capital-intensive processes of continuous slab casting, slab reheating, and hot rolling. Near net shape casting uses 25% less energy than the current best practice conventional technology. The first commercial application, thin slab casting, was introduced in 1989 and now accounts for one-quarter of all U.S. thin slab production capacity. Using this technique, sheet steel can be produced at a cost of $250/ton compared to conventional technology costs of $350/ton.

4.4.8 Metal Casting

Metal casting is not a single industry segment according to the SIC system, but covers a diverse group of products and metals. Products range from cast pipes, motor vehicle components, and tools. Iron, steel, aluminum, copper and zinc are all metals used by the industry. The industry is labor intensive, with many small plants; four out of five have fewer than 100 workers. Over half of the energy use is in melting metal. Technologies which improve the melting stage or reduce waste/recasting have important energy implications.

4.4.8.1 Computer-Aided Casting Design

Rapid advances in computer modeling of the casting process and in computer-aided drafting of castings have led to an increased use of computers in foundries, and hence, an increased need for integration in casting design systems. Increased integration in the casting design functions is needed to realize the full potential for improving both casting designs and production lead time. Two kinds of information are produced by the casting analysis and simulation function: (a) predicted outcome of casting the current design; and (b) the processing parameters for the casting process, if the casting design appears sound. The predictive results allow the foundry engineer to evaluate the filling of the mold cavity, the potential for defects such as porosity in the casting to occur, the sequence of solidification, and the time for complete solidification. With computer modeling, an average of 25% improvement was found in casting yield (Lensen 1996, Lensen et al. 1995), which would comparably reduce energy use for metal remelting.

4.4.8.2 Optimized Coreless Induction Melting

Most foundries can dramatically reduce a major portion of their energy through optimization of their induction melting equipment. It has been estimated that foundries are only operating their induction furnaces at 50-80% of their optimal efficiency (Horwath et al. 1996). A foundry melting 1000 tons/month could reduce its monthly melting costs by $5/ton by installing sensors and computer optimization of its melting practice. Four major variables are important in determining the power required for melting: (1) charge makeup, (2) furnace cover, (3) power application, and (4) furnace condition. In some cases, optimal material use resulted in higher energy use (22% more). Use of a furnace cover reduced energy consumption by 12%. Furnace condition (i.e., hot, medium, or cold) interacts with the charge to significantly affect energy consumption. Maintaining the furnace in hot condition resulted in 15.4% less energy consumption for melting the charge (Horwath et al. 1996).

4.5 THE LONGER TERM: FUTURE TECHNOLOGIES AND R&D POTENTIAL

The technologies cited above are currently available, or soon will be, because of past R&D. For future technologies to contribute to increased energy and emissions reductions presumes a continued stream

of R&D activities into the future. Recent efforts by the Department of Energy are directed at ensuring that steady stream of R&D by partnering with industry.

The Office of Industrial Technologies, in an effort to garner support and make their research and development activities more in line with the needs of industry, has initiated a joint government-industry planning process called the "Industries of the Future." The vision of the way that future industry will function and the technologies that the industry will use shapes, in part, the organization and implementation of government R&D efforts. It is this process that may lead to an invigorated effort to develop future technologies that will improve energy efficiency and reduce carbon emissions.

In this section we discuss the potential for additional decreases in energy intensity in the future as a result of the continuation of future R&D efforts. Here we draw heavily on the vision documents that have been published or are being prepared by the energy-intensive industries under the OIT's Industries of the Future process. We discuss general areas of potential advancement or provide specific examples of some of the technologies or technology areas that show particular promise for reducing energy consumption and concomitant greenhouse gas emissions.

4.5.1 Pulp and Paper

The Vision process for the Forest Products Industry of the Future was developed by the industry in collaboration with the Department of Energy's Office of Industrial Technologies, and is called "Agenda 2020 – A Technology Vision and Research Agenda for America's Forest, Wood, and Paper Industry." Two of the major concerns of this document are Environmental Performance and Energy Performance. One way these objectives might be met is through the use of polyoxometalate bleaching.

4.5.1.1 Polyoxometalate Bleaching

Traditionally, the last remnants of lignin from the pulp have been removed with a chlorine bleaching process. However, the environmental impacts of chlorine have lead to significant efforts to find alternative methods to produce a desirable soft white fiber. Among these have been ozone bleaching and peroxide bleaching. Unfortunately, nothing has come to market which is as effective and selective as chlorine or chlorine dioxide. Polyoxometalates may be just such a new process. They are highly selective and can be regenerated within the process. In addition to desirable performance characteristics, the polyoxometalate system is consistent with the goals of increasing recycling of process water and reducing the effluent load from pulp mills. Compared to chlorine based systems, the new process promises to reduce electrical energy consumption of pulp bleaching by 50%.

4.5.2 Chemicals

4.5.2.1 Biological/Chemical Caprolactam Process

Nylon-6 is currently produced from caprolactam. The chemical synthesis of caprolactam from cumene is a complex, multi-step process that is energy-intensive and generates considerable waste. Nylon-6 could also be produced from caprolactone. However, the current market price for caprolactone makes this route uneconomical.

A laboratory-demonstrated biological process has been developed that would provide a one-step, cost-effective production process for caprolactam manufacture that requires 50% less energy than the current process, costs half as much (considering both capital and energy costs), and produces almost no waste byproducts. Research on this process has established the technical feasibility of the biomanufacturing process for converting inexpensive cyclohexane into caprolactone. Under this project, the feasibility of the laboratory-demonstrated biomanufacturing process was established, and

the process is now available to be optimized for possible scale-up to pilot plant scale. It is estimated that, by the year 2020, this technology can provide annual energy savings of 12 trillion Btu (DOE 1997). While this is a modest total savings (the chemical industry used over five quads in 1991), this is just one of tens of thousands of chemical processes.

4.5.2.2 Flexible Chemical Processing of Polymeric Materials

Waste textiles and recycled waste materials from automobiles, appliances, and furniture contain polymers (such as nylon-6, nylon-66, PET, and polyurethanes) that can be converted into valuable chemical feed stocks. However, processes that can only convert a single type of recycled material can face high costs for material collection and for transportation of the resulting feed stocks. Because these costs are the major contributors to process costs, processes are needed that can convert a variety of recycled materials.

Research in this area is working toward developing a thermochemical process that can convert a wide variety of recycled materials into valuable chemicals. A two-stage process is envisioned: the first will use selective catalytic pyrolysis to recover chemicals such as caprolactam, hexamethylendiamine, and dimethyl-terephathalate; the second will convert the unreacted organic material into synthesis gas, which can be converted to a variety of chemicals of use to the chemical industry.

Because the process can address a wide variety of recycled materials, large regional recycling plants can be developed, lowering material collection and transportation costs, and thereby increasing the viability of recycling many materials. It is estimated that, by the year 2020, the use of this technology will save 265 trillion Btu annually (DOE 1997).

4.5.2.3 Genetic Engineering

Many chemicals firms are investing heavily in genetic engineering and, over the next decade, many expect to commercialize products. Low-carbon biotechnologies include engineered plant systems to allow crops to fix their own nitrogen from the air (thus avoiding N_20 emissions associated with fertilizer manufacture); agricultural "petroleum plants" that grow feed stocks for the chemicals industry; and intermediate products such as polymers.

4.5.3 Petroleum Refining

The National Petroleum Council issued a report in 1995, "Research, Development, and Demonstration Needs on the Oil and Gas Industry", which identifies the future of the industry in 2020. It stresses, among other things, the need for flexibility in processes as well as new chemistries and materials. Changing input feed stocks and environmental requirements will tend to push the industry toward higher energy use in 2020, without developments such as new catalysts or other process changes that are on the horizon.

4.5.3.1 Development of Improved Catalysts

The purpose of a catalyst is not to lower the energy needs of a reaction (which are governed by thermodynamics) but to lower the energy required to activate a process and thereby increase the kinetics and/or product selectivity. If it accomplishes either or both of these tasks, the energy demands on a given process should decrease either due to lower heat demand (lower energy of activation) or from greater throughput. Most of the energy use in a refinery that could benefit from improvements in catalyst technology is consumed in one of three major process areas: (1) hydroprocessing, (2) catalytic cracking, and (3) alkylation.

In hydroprocessing, much energy is utilized in heating up heavy oils and resids to temperatures at which the catalyst activity is high enough. Additional energy is expended in the compression of hydrogen to pressures up to 2000 psi. Improved catalysts (capable of functioning at lower temperatures and pressures) could reduce the energy used by decreasing the reaction temperature of this process.

Energy usage could be improved for catalytic cracking in terms of product selectivity. Cracking catalysts are extremely efficient at converting "good" gas oils to gasoline and distillate. However, when significant fractions of resid and the metals that accompany these resids are used as fluid catalytic cracking (FCC) feeds, the selectivity (in terms of gasoline yield) drops precipitously. This gasoline loss comes at the expense of increased coke and dry gas production, which in turn requires catalyst coolers in order to keep the temperature of the catalyst bed down (required by increased coke burn) and higher compressor capacity to handle the increased dry gas yield. If catalysts were designed to handle higher amounts of heavy oils without the detrimental effects outlined above, then more resid could be handled in the highly efficient FCC with resulting decreased utilization of the less efficient hydrotreaters.

The largest energy demand in the alkylation units are in the refrigeration units used to keep the hydrofluoric acid temperature down. Here the need is for a catalyst which will operate at temperature above ambient. Many solid alkylation catalysts which are in pre-commercial testing and evaluation function at temperatures around 150°C. Many of the streams requiring alkylation are at or near this temperature when they exit their respective processing units. Such heat is normally considered waste heat and thus could easily be utilized for the alkylation process. Therefore, even though the reaction temperature would go up, the energy demand would decrease.

4.5.4 Glass

The glass industry vision of itself in 2020 is defined in "Glass: A Clear Vision for a Bright Future". This vision document includes, as one of many goals, reducing process energy use from present levels to 50% toward the theoretical limit of 2.2 million Btu required to melt a ton of glass. On April 29, 1996 a compact between the DOE and the major glass producing companies was signed to enable collaboration in such areas as waste reduction, energy efficiency, and quality control. The technology road map is currently under preparation. The technologies below are just a few examples of areas of glass industry technology development.

4.5.4.1 Optimizing Electric Boost to Reduce Total Energy Consumption

High energy efficiency, through conversion of electric energy into useful heat, and low volatilization are the primary advantages of electric melting. Current operating practice has shown that effective use of electricity near the back end of the furnace, where the batch is added, can reduce fossil fuel needs. Research needs for optimizing electric boost include, but are not limited to, investigating new electrode and electric arc melting processes, modeling of the current technology to fine-tune operation conditions, such as energy inputs and locations of the electrodes, and improving the electrode control system (Glass Industry Working Group).

4.5.4.2 Recovering and Reusing Waste Heat from Oxy-Fired Furnaces

Recovery and reuse of waste heat from the oxy-fuel process will further increase energy efficiency of the process. Preheating the batch and cullet, described above, is one method to recover heat from the flue gas. Other options, such as regenerative oxygen heat recovery (Browning and Nabors 1996) and a "synthetic air" concept (Argent 1997), have been proposed and need to be tested and evaluated. A Thermal Swing Adsorption (TSA) oxygen production process has been demonstrated in the laboratory

with enrichments of up to 89%. The process is based on synthetic chemicals that can reversibly bind oxygen at low temperatures and release it at elevated temperatures. The operation is in a temperature range of 70° to 220°F, so low grade waste heat can be used to drive the process, and the external energy required for produce oxygen can be reduced.

4.5.5 Iron and Steel

"Steel – A National Resource for the Future" broadly defines four areas of R&D to shape the industry in 2020. These include production efficiency (which encompasses energy efficiency), recycling, environmental engineering, and product development. The goal of increasing steel production to over 70% of recovered scrap would have major implications for energy use. DOE and the two major steel industry trade groups have signed a R&D collaborative compact to work together on the first three of the four research areas. Below, we discuss some of the process areas within which energy and other savings are likely to be achieved from technical breakthroughs.

Activity will be largely dictated by the viability of different iron making processes that are under development. R&D effort should focus on developing a process scheme that incorporates both iron making and steel making into one system with thin strip casting as a final product. The effort should incorporate a coal-based reductant process which can be coupled with steel making operations and simultaneously produce power in a combined cycle that includes both gas and steam turbines.

Steel making processes currently utilize computer technology, primarily to implement prespecified procedures in a timely manner. There is very little feedback in these systems to either enhance process efficiency or improve the product quality. Key process parameters should be identified so that interactive logic and high-speed computer systems can be used to control/modify/maintain these process parameters to obtain a quality product. Such an intelligent-processing approach is essential for the production of so called "cleaner steel" with low residual elements.

The development of sensors for all aspects of process control and for enabling process changes with a feedback system is essential for improving process efficiency and optimizing different stages of the melting, casting, thermomechanical processing, and final heat treatment. Applications of novel ideas and approaches need to be explored and transfer of technologies available from defense and chemical processing industries may be a fruitful approach.

4.5.6 Metal Casting

A diverse group of CEOs and presidents from the foundry, die casting, and foundry supply companies co-authored "Beyond 2000: A Vision for the American Metal Casting Industry." This vision of the industry identifies six critical areas: production efficiency; recycling; pollution prevention; application development; process controls; and new technology development. The specific goals include increasing productivity by 15% and reducing energy consumption by 3-5% by 2010. The Cast Metals Coalition is preparing a R&D strategy to achieve these and other goals identified in the industry vision. Some examples of technology areas are given below.

Electromagnetic Casting: An electromagnetic field in a casting is used to induce eddy currents in the liquid metal that, together with the field, stir and contain the liquid metal in the casting. Two examples are discussed below:

EM Stirring: In continuous casting, the solidification process can be improved by EM stirring, producing better metallurgical results, improved internal quality of the casting, and even reduced meniscus instability and surface defects (Beitelman and Mulcahy 1994, Chang et al. 1995). The benefit

from EM stirring takes the form of reduced wastage per cast. As a minimum, we expect that the present average yield of 55% for the industry can be increased to 65%, a savings of 130,000 tons per year, with an associated energy savings of 25 trillion Btu per year (American Foundrymen's Society 1995).

EM Confinement: In the presently dominant sheet-forming process, thick steel slabs are cast and then hot-rolled. Twin-roll casting with EM confinement has the potential to cast thin sheets by eliminating the hot-rolling stage, giving the sheet product an enormous economic advantage over products made by competing methods (Saucedo and Blazek 1994, Blazek et al. 1994) and completely by-passing an energy-intensive stage of production.

4.6 CONCLUSIONS

This chapter presents an approach to assessing the potential for efficiency to reduce energy use in the most diverse sector of the economy, the industrial sector; this approach represents a compromise between the desire for technology detail and the need to evaluate sector-wide energy use. The approach uses two publicly available models, Argonne's Long-term Industrial Energy Forecasting (LIEF) model and the Energy Information Administration's industrial module from the National Energy Modeling System (NEMS), to simulate a plausibly optimistic set of scenarios for additional energy savings, relative to an established base case (AEO97). The models are used to project what energy savings could arise from an 'invigorated effort' to put currently available or near commercial technologies into practice in industry. This invigorated effort is loosely characterized by either a combination of new policy initiatives or a more serious consideration of efficiency as a strategic concern of industrial decision makers.

Two efficiency cases are presented in order to project overall reductions in energy use by 2010. A reduction of 5-10% is projected to be technically feasible, given adequate policies or other incentives to expand the adoption of cost-effective measures. This is about 2.5 quads in the high case. The LIEF model projects that these reductions could arise from cost-effective investments defined by a capital recovery factor of 15% (about a seven year pay-back). The LIEF model does not assume that in every case all energy-efficiency investments are made, but an increased penetration rate of efficiency investment is assumed relative to the base case as a result of this 'invigorated effort'. For many of the energy-intensive industrial sectors, these projected energy savings are consistent with roughly doubling the current rates of capital stock replacement or doubling the rate of energy technology efficiency improvement that is currently represented in the NEMS model.

Since the models used to conduct the scenario analysis do not have a detailed, technology-specific representation of each major industrial sector, the chapter also provides illustrative examples of technologies for most of the energy-intensive industries. These are examples of technologies that have the potential to reduce energy use relative to current practices if widely adopted. These technology examples exhibit substantial energy savings relative to current industry practice, so they reinforce the fact that the model results are feasible. But one cannot expect these technologies to be adopted widely unless there is some invigorated effort to encourage their adoption. The slow turnover of the capital stock in the energy and capital intensive industries is one reason that this invigorated effort would be needed. Under conservative projections, in the near-term, many of these technologies (and the many others not listed here) are capable of reaching high levels of penetration but most will not achieve 100% penetration. However, the examples show that there are many ways in which efficiency in industry can be increased, given the right incentives; the examples help establish the technical plausibility of the projections.

The efficiency case projections also show that, on a percentage basis, there are more savings in 'light' non-energy-intensive industry vs. the 'heavy', energy-intensive sectors. This result arises from the LIEF model scenarios but, due to the structure of the model, does not have an analog in NEMS. Because the share of total production costs attributable to energy use in the non-energy-intensive sectors is very low (the manufacturing average is about 3% and most light industry is less), it is not surprising that the range of energy performance is quite broad. Energy-efficient technologies, in the form of motor systems as well as lighting and HVAC options (similar to those discussed in the commercial section of Chapter 3), represent cost-effective investment opportunities in light manufacturing. However, there may not have been a managerial or technical focus on energy efficiency in those industries. An 'invigorated effort' could provide this focus. On the other hand, to reduce energy use in 'heavy' industry, where considerable attention to efficiency has already been paid, low capital turnover rates and difficulty in financing medium to large investments may be the major impediments to accelerated improvements in energy utilization. This 'invigorated effort' in these sectors might require tax incentives, alternative financing arrangements, new developments that lower first cost, or demonstration projects that lower perceived risk. The diversity among these broad categories of industry implies that the mix of policies required to achieve the high-efficiency case may differ for the various types of industries, based on their current business and technical practices as well as current domestic and international market conditions.

For all of the industries discussed above, further progress in energy efficiency beyond 2010 requires further developments in technology. These developments may be *incremental* improvements (e.g., sensors, controls, and system/process modeling) or may be *fundamental* breakthroughs (e.g., catalysts, direct smelting, or bioprocessing). Incremental improvements need not be associated with 'small' efficiency changes. The ability to sense and adjust a process to achieve optimal operating conditions can have large effects on productivity and energy consumption. However, the search for totally new methods to produce a product with fundamental breakthroughs in chemistry, metallurgy, or biology offers another route to enhance productivity and lower energy use. These two avenues of R&D to create the manufacturing sector of 2020 are both being sought by private and private/public partnerships.

Table 4.15 summarizes the technology examples presented above. A rough categorization of incremental (I) and fundamental (F) has been made. Many of the underlying concepts in the examples apply to other sectors, while others are very process specific. This identification is made as well. In should be noted that the year 2010 designates current (on very near commercial) technologies, while the year 2020 designates technologies that will require further R&D, with no prediction of a commercialization date.

The range and types of technological solutions in industrial applications is quite large. Since energy represents a cost, and energy efficiency a potential source of profit, these technical solutions can fit within the economic goals of business. With the right incentives, higher energy efficiency of the magnitude projected here in the industrial sector is an achievable goal.

Table 4.15 Summary of Technology Examples

Example Taken From	Technology Example	Year	Type of change: incremental or fundamental	Concept applicable to other sectors	Saves fossil or electric energy
Aluminum	Improve Furnace Efficiency	2010	I	Y	EF
Aluminum	Materials Recycling	2010	I	Y	E
Aluminum	Improving Hall-Heroult Cell Efficiency	2010	I	N	E
Aluminum	Wettable Cathodes	2010*	I	N	E
Aluminum	Inert Anodes	2010*	I	N	E
Chemicals	Pinch Analytical Techniques	2010	I	Y	F
Chemicals	Advanced Distillation Control Techniques	2010	I	N	F
Chemicals	Flexible Chemical Processing Of Polymers	2020	F	N	F
Chemicals	Biological/Chemical Caprolactam Process	2020	F	N	F
Cross-cutting	Combined Heat and Power	2010	I	Y	EF
Cross-cutting	Motor Systems	2010	I	Y	E
Glass	Glass Batch/Cullet Preheater Technology	2010	I	Y	F
Glass	Advanced Burner Technology	2010	I	Y	F
Glass	Oxy-Fuel Process	2010	I	N	F
Glass	Producing Oxygen More Efficiently	2020	I	Y	E
Glass	Recovering Waste Heat	2020	I	Y	F
Glass	Maximize Combustion Efficiency	2020	I	Y	F
Glass	Optimizing Electric Boost	2020	I	N	F
Iron and Steel	Process Controls	2010	I	Y	EF
Iron and Steel	Hot Connection	2010	I	Y	F
Iron and Steel	Scrap Preheating	2010	I	Y	EF
Iron and Steel	Use Of DC, Rather Than AC, EAFs	2010	I	N	E
Iron and Steel	Coal Or Natural Gas Injection	2010	F	N	F
Iron and Steel	Direct Smelting /Reduction	2010	F	N	F
Iron and Steel	Process Controls And Sensors	2020	I	Y	EF
Iron and Steel	Direct Smelting & Thin Strip Casting	2020	F	N	EF
Metal Casting	Computer-Aided Casting Design	2010	I	Y	EF
Metal Casting	Optimized Coreless Induction Melting	2010	I	N	E
Metal Casting	Electromagnetic Stirring	2020	I	N	EF
Metal Casting	Electromagnetic Casting	2020	F	N	EF
Petroleum Refining	Utility System Improvements	2010	I	Y	F
Petroleum Refining	Process/Equipment Modifications	2010	I	N	F
Petroleum Refining	Development Of Improved Catalysts	2020	F	Y	F
Pulp and Paper	On-Machine Sensors For Paper Properties	2010	I	Y	F
Pulp and Paper	Multiport Cylinder Drying	2010	I	N	F
Pulp and Paper	Impulse Drying	2010	I	N	F
Pulp and Paper	Biomass Gasification	2010*	I	Y	EF
Pulp and Paper	Black Liquor Gasification	2010*	I	N	EF
Pulp and Paper	Sulfur Free Pulping	2020	F	N	EF
Pulp and Paper	Polyoxometalate Bleaching	2020	F	N	EF

* Based on the accelerated deployment described in Section 4.3.

4.7 REFERENCES

Aluminum Association, "Patterns of Energy Usage in the U.S. Aluminum Industry, Full Year - 1989," August, 1991.

Aluminum Association. 1993. Aluminum Statistical Review for 1992, Aluminum Association, Washington, D.C.

American Foundrymen's Society. 1995. *Foundry Industry Research Plan.*

American Metal Market. 1997. *Metal Statistics, 1997: The Statistical Guide to North American Metals, 89th Edition* (New York, NY: American Metal Market, Chilton Publications): p. 113.

Argent , R.D. 1997. "Synthetic Air" for Oxy-Fuel Glass Melting Furnaces with Filtration and Regeneration," Presented at the Annual Meeting of the Society of Glass Technology, January 17, 1997, Clearwater, FL.

Beitelman, L. and J. A. Mulcahy. 1994. "Flow Control in the Meniscus of Continuous Casting Mold with an Auxiliary A.C. Magnetic Fields," *International Symposium on Electromagnetic Processing of Materials, EPM'94*, Iron and Steel Institute of Japan, pp. 235-241.

Blazek, K. E., H. G. Gerber, and I. G. Saucedo. 1994. "Application of Alternating Magnetic Fields for Edge Containment in Strip Casting," *International Symposium on Electromagnetic Processing of Materials, EPM'94*, Iron and Steel Institute of Japan, pp. 197-202.

Boyd, G., J. Molburg, P. Thimmapuram. 1996. *Investigating Cogeneration Potential Using Industrial Fuel Use Data*, draft report, Argonne National Laboratory, Argonne, IL.

Brent, R. And K. Davidson, *Market Outlook and Application for Industrial Gas Turbines in Distributed Generation*, paper presented at the Fortieth Annual Engineering and Operations Workshop, American Public Power Association, Salt Lake City, UT, March 25-28, 1996.

Browning, R. and J. Nabors. 1996. "Regenerative Oxygen Heat Recovery for Improved Oxy-Fuel Glass Melter Efficiency," Presented at the 57th Conference on Glass Problems, October 8th and 9th, 1996, Columbus, OH.

Burgmann, W. and B.B. Pelts. 1995. "Scrap preheating shaft furnaces - development and results," *Steel Times International*, **19**(1):16-17, Jan.

Carmichael, I.F. 1992. "An Introduction to Blast Furnace Coal Injection," *Iron & Steelmaker*, **19**(3):67-73.

Carroll, Peter, Solar Turbines, Personal Communication, May 1997.

Carroll. P., and K. Davidson, *The Role for Advanced Turbine Systems in Atmospheric Pollution Prevention*, presentation to the U.S. Department of Energy, Washington, D.C., May 15, 1997.

Center for Metals Production. 1987. *Technoeconomic Assessment of Electric Steelmaking Through the Year 2000*, EPRI EM-5445, Electric Power Research Institute, Palo Alto, CA.

Chang, F. C., J. R. Hull and L. Beitelman. 1995. "Simulation of Fluid Flow Induced by Opposing AC Magnetic Fields in a Continuous Casting Mold," *Process Technology Conference Proceedings*, Vol. 13, Iron and Steel Society, pp. 79-88.

De Beer, J.G., M.T. van Wees, E. Worrell, and K. Blok. 1994. *The Potential of Energy Efficiency Improvement in the Netherlands up to 2000 and 2015*, Utrecht University, Utrecht, Netherlands.

Decision Analysis Corporation, *NEMS Industrial Module: Methodology to Incorporate the ABMA Boiler Database*, December 14, 1995.

Dillich, S., Personal Communication, May 27, 1997.

Eisenhauer, J.et al, *Report of the Aluminum Technology Roadmap Workshop, November 19-20, 1996*, Alexandria, Virginia. Energetics, Inc. Columbia MD, February 1997.

Emad, F. et al. 1996. "In-Line Inspection of Carbon Anodes for Use in Aluminum Production," *Light Metals 1996.*

Energetics, Inc. 1990. Industry Profiles Final Report: Energy Profiles for U.S. Industry, prepared for the Office of Industrial Technologies, U.S. Department of Energy, Columbia, MD.

Energetics, Inc. 1997. Aluminum Technology Roadmap Workshop, Final Draft, Report of the Aluminum Technology Roadmap Workshop, November 19-20, 1996, Alexandria, Virginia, Columbia, MD.

Energy and Environmental Analysis, Inc., Industrial Market Evaluation, Topical Report, *Analysis of the Industrial Boiler Population*, prepared for the Gas Research Institute, Report # GRI-96/0200, June 1996, Chicago, IL.

Energy Information Administration, 1997, Manufacturer's Energy Consumption Survey, 1994. MECS 1997 U.S. DOE, Washington D.C. preliminary tables available on the Internet. http://www.eia.doe.gov

Energy Information Administration (EIA). 1994. *Manufacturing Consumption of Energy: 1991*, DOE/EIA-0512(91), Washington, D.C.

Energy Information Administration (EIA). 1996. *Emissions of Greenhouse Gases in the United States*, DOE/EIA-0573(95), Washington, D.C.

Energy Information Administration (EIA). 1997. *Annual Energy Outlook 1997, with Projections to 2010.* DOE/EIA-0383(97). Washington, D. C.

Etienne, A. and W.R. Irving. 1985. "The Status of Continuous Casting," in Institute of Metals, 1985, *Continuous Casting '85*, conference proceedings May 22-24, 1985, London, UK.

Evans, J.W., "Electricity in the Production of Metals: From Aluminum to Zinc", *Metallurgical and Materials Transactions B.* Volume 26B, April 1995 pp 189-208.

Gas Research Institute, Final Draft of the *1998 Edition of the GRI Baseline Projections*, Arlington, VA, September, 1997.

Gas Research Institute, *Light Duty Vehicle Full Fuel Cycle Emissions Analysis*, 1994.

Gee, J.T. et al, "Long-Term Testing and Evaluation of Cathode Components in a Commercial Aluminum Cell," August 1989, Great Lakes Research, DOE/IE/12689-1; Church, K.D. et al, Addendum DOE/ID/12689-1 (vol-Add.).

Geiger, G., ed. 1996. "Glass Problems Conference Focuses on Oxy-Fuel," *The American Ceramic Society Bulletin*, Vol. 75, No. 3, March.

General Electric, 1997, secondary source from Solar Turbines and Onsite Energy Presentation to the U.S. Department of Energy, May 1997.

Gibbs, M. and C. Jacobs. 1996. "Reducing PFC Emissions from Primary Aluminum Production in the United States," *Light Metal Age*.

Glass Industry Working Group. Adapted from discussion in the Energy Efficiency and Conservation Subcommittee.

GRID. 1996. "License Granted to Corning, Inc.," Summer.

Haissig, M. 1994. "The d-c shaft furnace," *Iron and Steel Engineer*, May, pp. 25-27.

Haupin, W. E., "Principles of Aluminum Electrolysis," *Light Metals*, 1995.

Heffron, J., R. Hewertson, and E. Riley. 1993. "Benefits to Aluminum Furnaces Through Oxygen-Assisted Melting," in Proceedings of the 8th International Sheet & Plate Conference, Louisville, KY, October 5-8, 1993, Aluminum Association, Washington, D.C.

Hogan, W.T., and F.T. Koelble. 1996. "Fewer blast furnaces, but higher productivity," *New Steel*, November.

Horwath, J. A., T. Klemp III, and J. M. Svoboda. 1996. "Variables Identified for Optimal Coreless Induction Melting", *Modern Casting*, May, pp. 33-35.

International District Energy Association, *Encouraging Supply-Side Energy Efficiency in Federal Restructuring Legislation*, White Paper, February 20, 1997 Washington D.C..

Jeltsch, R., and T. Franklin. 1992. "Retrofit of Kaiser's Mead Smelter," in Light Metals, Proceedings of the 121st TMS Annual Meeting, San Diego, CA, March 1-5, 1992, Minerals, Metals, & Materials Society, Warrendale, PA.

Kenchington, H, et al, Reduced Greenhouse Gas Emissions through Advanced Aluminum Cell Technology. DOE proposal, April 1997.

Larson, E.D. 1991. Biomass-Gasifier/Gas-Turbine Cogeneration in Pulp and Paper Industry. ASME paper International Gas Turbine and Aeroengine Congress and Exposition, Orlando, FL. June 3-6, 1991.

Lensen, D. H. 1996. "Survey Provides Profile Casting Design Software Use", *Modern Casting*, September, pp. 29-31.

Lensen, D. H., C. Beckermann, and G. W. Fischer. 1995. "Implementation Issues for Computer-Aided Casting Design", Summary Report to American Metalcasting Consortium.

Livesay, P., "Strength Characteristics of Portland-Limestone Cements," Construction and Building Materials, 5(3), pp. 147-150, 1991.

Lympany, S.D. and J.W. Evans: *Metallurgical and Materials Transactions B.*, 1983, vol. 14B, pp. 63-70.

Major, Graham, *Learning from experiences with small-scale cogeneration*, Centre for the Analysis and Dissemination of Demonstrated Energy Technologies, *CADDET, 1995, The Netherlands.*

Major, W and K. Davidson, *Gas Turbine Power Generation: Environmental Analysis and Policy Considerations*, DRAFT Report by Onsite Energy Corporation prepared for Oak Ridge National Laboratory, February 19, 1997a.

Major, W. and K. Davidson. 1997b. "Gas Fired Power Generation: Environmental Analysis and Policy Consideration," draft report by Onsite Energy, Carlsbad, CA, prepared for the U.S. Department of Energy, Office of Industrial Technology.

Major, W., *Basis for 60 GW of Remaining Cogeneration Potential in the Industrial Sector* May 22, 1997.

Margolis, Nancy., Personal Communication. 1997.

Mathur , V.K. date? *Thermal Swing Absorption Process for Oxygen Separation from Air*, DOE/CE40927-3, Prepared for U.S. Department of Energy, Office of Industrial Technologies.

Miller Freeman, Inc., 1972-1997 *North American Pulp and Paper Fack Books*, San Francisco.

Nelson, Kenneth E. 1993. "Creating an Empowered Conservation Culture," *Proceeding of the Workshop on Partnerships for Industrial Productivity through Energy Efficiency*, pp. 209-224, September 19-22, Portland, OR.

Newsted, G., H. Meyer, R. Hawkins, and J. Johnson. 1992. "Twenty-Five Years of Progress at Intalco," in Light Metals, Proceedings of the 121st TMS Annual Meeting, San Diego, CA, March 1-5, 1992, Minerals, Metals, & Materials Society, Warrendale, PA.

Onsite Energy, *ATS Market Assessment*, 1994.

Onsite Energy. 1997. Gas Turbine Environmental Analysis and Policy Considerations.

Parks, W., Personal Communication, May 16,1997.

Parks, William, Personal Communication, July 17, 1997

Portland Cement Association, Economic Research Department, Skokie, Illinois, 1996d.

Portland Cement Association, Potential Reduction of CO2 Emissions in the Manufacture of Portland Cement (R&D No. 2010), Research and Development Department, PCA, Skokie, Illinois, 1996a.

Portland Cement Association, Properties of Concretes Made with Fly Ash and Cements Containing Limestone (R&D Serial No. 2052a), Research and Development Department, PCA, Skokie, Illinois, 1996b.

Portland Cement Association, The Reduction of Resource Input and Emissions Achieved by Addition of Limestone to Portland Cement, Research and Development Department, PCA, Skokie, Illinois, 1996.

Portland Cement Association, The Use of Limestone in Portland Cement: A State-of-the-Art Review (PCA Serial No. 2025a), Research and Development Department, PCA, Skokie, Illinois, 1996c.

Reed, J., Personal Communication, May 21,1997.

Richards, N., 1994, "Strategies for Decreasing the Unit Energy and Environmental Impact of Hall Heroult Cells," *Light Metals* 1994.

Romm, Joseph, Personal Communication, July 17, 1997

Ross, C.P. 1996. "Oxy-Fuel Conversion Challenges for Glass Manufactures," Presented at American Flame Research Committee Meeting, May 6-7, 1996, Orlando, FL.

Ross, M. 1990. "Capital Budgeting Practices of Twelve Large Manufacturers", in *Advances in Business Financial Management*, Ed. Philip Cooley, Dryden Press, Chicago.

Ross, M., P. Thimmapuram, R. Fisher, W. Maciorowski. 1993. *Long-Term Industrial Energy Forecasting (LIEF) Model (18-Sector Version)*, ANL/EAIS/TM-95, Argonne National Laboratory, Argonne, IL.

Saucedo, I. G. and K. E. Blazek. 1994. "Development of an Electromagnetic Edge Dam for Twin-Roll Casting," *METEC-94*, pp. 457-462.

Sauer, G. "Cement, Concrete and Greenhouse Gas" paper presented at the CGLI Second Roundtable on North American Energy Policy, April, 1997.

Scheidig, K. 1995. "Hot metal from oxygen cupola furnaces as an alternative charge material for electric arc furnaces," *Stahl und Eisen*, 15 May, **115**(5): 59-64.

Steinmeyer, Dan. 1997. Proceedings of the 1997 ACEEE Summer Study, July 8-11, Saratoga Springs NY.

Tresouthich, S.W. and Mishulovich, A. "Energy and Environmental Considerations for the Cement Industry, " Proceedings of the Energy and the Environment in the 21st Century Conference, Cambridge, MA, 1990.

U. S. Department of Agriculture (USDA). 1990. *An Analysis of the Timber Situation in the United States: 1989-2040*. Technical Report RM-199.

U. S. Department of Energy (DOE). 1987. *A Guide to Investment Appraisal of Energy Efficiency Projects in the Steel Industry*, Energy Efficiency Office, Washington, D.C.

U.S. Department of Energy (DOE). 1995. *Energy Conservation Trends: Understanding the Factors Affecting Energy Conservation Gains and Their Implication for Policy Development*, DOE/PO-0034, Washington, D.C.

U.S. Department of Energy (DOE). 1997. *1996 Chemicals Team Annual Report*, Office of Industrial Technologies, Washington, D.C.

U.S. Department of the Interior, Bureau of Mines (DOI). 1993. *Aluminum Availability and Supply: A Minerals Availability Appraisal*, Information Circular 9371, Washington, D.C.

U.S. Department of the Interior, Bureau of Mines (DOI). 1994. Mineral Commodity Summaries: 1994, Washington, D.C.

U.S. Environmental Protection Agency (EPA), 1996. *Primary Aluminum Industry: Technical Support Document for Proposed Maximum Available Control Technology (MACT) Standards.*

U.S. Environmental Protection Agency, 1995, *Profile of the Nonferrous Metals Industry*, EPA 310-R-95-010.

Weyerhaeuser, Stone and Webster, Amoco, and Carolina Power and Light. 1995. *New Bern Biomass to Energy Project: Phase 1. Feasibility Study.* NREL/TP-42-7942

Wilken, L and R. Brent, Advanced Turbine Systems (ATS): A Partnership of the U.S. Department of Energy and Solar Turbines Inc. To Develop and Commercialize the Premier Power Source for the 21st Century., Solar Turbines, 960294/296, San Diego CA, 1996.

Windisch, C. and D. Strachan. 1991. Inert Electrodes Program, Fiscal Year 1990 Report, PNL-777, Battelle Pacific Northwest Laboratory, Richland, WA.

World Energy Council (WEC), 1995. *Energy Efficient Improvement Utilizing High Technology: An Assessment of Energy Use in Industry and Buildings*, London

ENDNOTES

[1] Because they become very important in a low-carbon scenario, we have made an exception to this approach in the case of low-carbon technologies which are examined from the bottom-up. Unlike energy-efficiency technologies, there is no established modeling procedure or analysis method for assessing the penetration of low-carbon (especially low process carbon) technologies. Thus, we simply provide case studies and take their results as a lower bound on the potential.

[2] Differences in the industry subsector detail prevented us from doing a precise calibration of the two models. It is not clear that such a calibration would substantially improve our analysis for these purposes.

[3] Technologies that supplement the existing process (e.g., process controls) might penetrate rapidly, but most that are replacements for existing process will more likely follow the 'normal' turnover patterns. Technologies achieving rapid penetration include sensors and process control software and technologies that can save significant amounts of energy.

[4] The forest products industry includes pulp and paper, as well as lumber and wood products. This report focuses on the relatively more energy-intensive pulp and paper segment of the forest product industry.

[5] In particular, we do not change the underlying forecast for activity in the refining sector.

[6] The HE/LC case also includes low-carbon technologies described in Section 4.4. These low-carbon technologies are not explicitly captured in the computer model runs.

[7] Not all energy-intensive industries are "heavy." The metal casting industry, for example, consists of many small shops owned by small businesses. It is important to distinguish OIT's Industries of the Future and the "heavy industry" of Table 4.1. These "heavy" industries include non-vision industries such as food (SIC 20), non-refining petroleum (SIC 295, 299), stone, clay and cement (SIC 324-329), non-aluminum non-ferrous (SIC 3331, 3339, 3351, 3356, 3357, 3364, 3366, 3369). Conversely, the vision industries include wood and lumber (SIC 24), miscellaneous paper (SIC 265, 267), and miscellaneous chemicals (SIC 283, 285, 2879, 289), which are not included in the "heavy" industry of Table 4.1.

[8] These numbers are calculated from the numbers in Appendix A for Figure 16 in DOE (1995).

[9] Note that, in Figure 4.3, ATS in simple cycle power-only mode has a higher heat rate than the most efficient combined cycle turbine. However, even the power-only ATS emits far less CO_2 than the existing sources of power to the grid. In our calculation of the carbon reductions for ATS in power-only applications, we make the conservative assumption that the ATS has about the same emissions as new power plants. The carbon savings in this market come only from avoided T&D.

[10] As an average of 3 to 18 MW units (9 to 80 MW in multiple units), ATS are 43% efficient in simple cycle and can be 80 – 85% efficient (combined thermal and electric efficiency) when used for cogeneration (Hoffman, 1997).

[11] Constraints to growth of cogeneration have derived in part from the traditional requirement that steam and electricity loads be matched to maintain efficient and cost-effective operation of the cogenerator. The new ATS overcomes this problem by running efficiently at a wide range of electricity to thermal ratios. Cogeneration has also been constrained by environmental permitting, utility regulation, and utility competition. Together these factors explain why very efficient CHP technology still comprises a relatively small fraction of electricity and steam generation. When policies to promote CHP are instituted, however, this fraction can grow dramatically (Major 1995). Finland, Denmark, and the Netherlands have each achieved a contribution of about 30% of electricity production based on CHP.

[12] In the recuperator configuration hot exhaust gas from the turbine is used to preheat the air leaving the compressor prior to combusion, thereby reducing the amount of fuel required to reach the design turbine inlet temperature.

[13] See Appendix D-3 for details.

[14] Such reform would include standardized permits to reduce costs for small sites and a life cycle approach that takes into account power plant emissions and T&D for on site power permits.

[15] Current regulations, and some proposed utility deregulation legislation, include barriers to small on-site CHP. Both scenarios assume policies that elicit the cooperation of utilities in the increase in on-site generation. One scenario that could be imagined is that the utilities themselves finance and service these industrial ATS's for CHP and power generation.

[16] Carbon reductions from fuel switching were not included – a conservative assumption discussed in Apendix D-3.

[14]The calculations performed for both scenarios were reviewed by the American Forest and Paper Association and industry representatives (David Cooper and Delmar R. Raymond).

[18] The makeup of residual biomass and residue generation rates in various forest product and paper industries are described in Appendix D-5.

[19] Three large plants in the U.S. manufacture adipic acid and they are working with the EPA to reduce emissions (Boyd 1997). However, emissions from this process have increased by 9.9% since 1990.

[20] Many of the U.S. aluminum smelters are located in regions of the country with large hydropower resources, notably the Pacific Northwest (served by the Bonneville Power Administration), the Southeast (served by the Tennessee Valley Authority), and Northern New York. Under both scenarios, the aluminum smelters that would likely be converted first would be those in regions such as the Ohio River Valley that are dominated by coal-powered plants.

[21] 0.2 MtC = [(5 plants) * (190,000 tonnes of AL/plant)* (13,200 kWh/tonne of AL) * (89 gr of carbon per kWh) * 0.17]/1,000,000 grams/tonne.

[22] The carbon savings from the aluminum industry efficiency improvements that are already included in Section 4.2.2 must be subtracted in order to identify the increment that can be added by this analysis of alternative aluminum production cells. We calculate this as follows. Table 4.2 estimates that the aluminum industry as a whole will be 2% more efficient in its use of electricity in 2010 under the efficiency scenario, compared to the business-as-usual case. Under the assumption here that 5 of 22 smelters (23%) will be retrofitted with wettable cathodes that offer a 17% improvement in electricity efficiency, the nation's aluminum smelters as a whole would be 3.9% more efficient (3.9% = 0.23 * 17%). This represents a 1.9% efficiency improvement (or 0.09 MtC of emissions reductions) over the 2% that is assumed in the efficiency case in Section 4.2.2.

[23] 0.48 = (5 of 22 plants) * (50%) * 4.2 MtC.

[24] 1.0 MtC = [(10 plants) * (190,000 tonnes of AL/plant)* (13,200 kWh/tonne of AL) * (160 gr of carbon per kWh) * 0.25]/1,000,000 grams/tonne.

[25] The carbon savings from the aluminum industry efficiency improvements that are already included in Section 4.2.2 must be subtracted in order to identify the increment that can be added by this analysis of alternative production cells. We calculate this as follows. Table 4.2 estimates that the aluminum industry as a whole will be 3.8% more efficient in its use of electricity in 2010 under the high-efficiency/low-carbon scenario, compared to the business-as-usual case. Under the assumption here that 10 of 22 smelters (45%) will be retrofitted with inert anodes that offer a 25% improvement in electricity efficiency, the nation's aluminum smelters as a whole would be 11.4% more efficient (11.4% = 0.45 * 25%). This represents a 7.6% efficiency improvement (or 0.67 MtC of emissions reductions) over the 3.8% efficiency improvement that is assumed in Section 4.2.2.

[26] 0.6 MtC = (10 plants) * (190,000 tonnes of Al/plant) * (0.33 tonnes of C/tonne of AL).

[27] 1.91 MtC = (10 of 22 plants) * (100%) * 4.2 MtC.

[28] Note that almost none of the carbon savings due to Section 4.2.2's high-efficiency/low-carbon (HE/LC) case should be subtracted from this amount. The clinker replacement is not an efficiency increase, but a demand reduction. Thus, the drop in carbon emissions is nearly additive. We subtracted a very small amount because of the 8.1% reduction in cement industry energy use under the HE/LC scenario. The carbon savings due to a 5-20% reduction in demand is 2-4 MtC depending on the kiln technology. The amount we subtracted is about 5% of the total (0.06-0.08 MtC). If we assume that the penetration by 2010 is limited to the European owned firms (roughly half), then the carbon reduction is 1-2 MtC. Note that the HE/LC energy efficiency savings of Section 4.2.2 are equivalent to a carbon emissions reduction of just over 1 MtC depending on cement kiln technology.

[29] The Greenville Tube Company (GT) realized non-energy benefits ten times greater than the energy benefits when the company upgraded its motors. GT is a manufacturer of high-precision, small-diameter, stainless steel tubing. GT replaced an old motor and inefficient eddy current clutch drive with an energy-efficient motor with vector control. This new motor required fewer runs and produced far less scrap than the old system. The motor reduced annual energy consumption by 37% and resulted in savings of more than $77,000 annually from increased productivity, reduced scrap generation, and reduced energy costs.