

THE WHITE HOUSE
WASHINGTON

To: Gene
Dan
Shulley
Peter D.
Bob B.
Jeff Smith

Date 8-7

From: The Staff Secretary

Here's summary
of a ready to be
released report from
DDE. Please take a look
so we can decide
best way to put it out.

WDS

FILE: Oram. R/KY/
5 LAB
REPORT

Proposed Media Roll Out for Five Laboratory Climate Change Study

THE NEWS

Peer-reviewed study demonstrates ability of U.S. industry to meet range of possible climate change commitments through development and deployment of technologies that increase efficiency and reduce emissions. The study's conclusions are clear: Clean energy technology can prevent climate change and contribute to economic growth. Industry can remain strong and competitive -- even with the challenges of reducing global pollution.

To illustrate study results -- and demonstrate that the technology solution is viable -- DOE has a set of additional, newsworthy announcements. For example:

- Clean diesel grant to Caterpillar and Cummins, reducing exhaust fumes
- Air conditioning standards for low-cost cooling -- less electricity means reduced emissions from power plants
- Climate technology grants to communities
- A call for proposals to develop technologies that recycle or isolate greenhouse gases, such as carbon emissions released by power plants.
- As many as 10 of DOE's 36 R&D 100 awards are technologies that contribute to reducing global warming. For example, Lawrence Berkely Laboratory's innovation reduces costs for applying energy efficient film on building windows.

ANNOUNCEMENT OPTIONS

1. Event or announcement by the Vice President with Secretary Peña

- DOE issues press release
- 2. New York Times exclusive on study only; broader announcement via press release*
 - Include presidential/vice presidential quote in release
 - Media conference call with Secretary Peña and WH principals
 - Follow up media by DOE, CEQ

3. New York Times exclusive on study only; broader announcement via Secretarial event

- President's quote in release
- Follow up media by DOE, CEQ
- Delay until September

FOLLOW UP MEDIA

Opinion editorial: Secretary Peña's byline

Editorial boards: Provide top 25 papers with release and studies...Calls by DOE/CEQ to Washington Post, New York Times...Mailings to Business Week, Automotive Week...

Columnists: Robert Samuelson...(add'l TBD)

Broadcast: Seek opportunities to discuss study on CNBC programs, Talk of the Nation (weekly or Friday science show), Diane Rehm, TechnoPolitics, etc.

Regional: Participating laboratories promote to regional media (New Mexico, Chicago, Tennessee, Denver, Washington State) -- via statements by lab directors, mailings/calls to editorial boards

SCENARIOS OF U.S. CARBON REDUCTIONS

Potential Impacts of Energy-Efficient and Low-Carbon Technologies by 2010 and Beyond

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

Oak Ridge
National Laboratory



Bringing Science to Life



Lawrence Berkeley
National Laboratory*

Pacific Northwest
National Laboratory

Operated by Battelle for the
U.S. Department of Energy

Pacific Northwest
National Laboratory



National Renewable
Energy Laboratory



Argonne National
Laboratory

DRAFT - August 1, 1997

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

*Coordinating laboratories for this study

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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 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 research, development, and deployment of clean technologies. Current projections suggest that a carbon emissions reduction of 380 million metric tons (MtC) 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 cost-effective 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 alone can reduce carbon emissions by 120 MtC by 2010. Under more aggressive assumptions motivated in part by a \$25/tonne carbon permit price, a combination of energy-efficient and low-carbon technologies can reduce 2010 emissions by a total of 230 MtC. Under a \$50/tonne carbon permit price, technology investments reduce 2010 emissions by about 380 MtC. 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 380 MtC/year by 2010) can produce benefits that exceed costs, counting as benefits only the energy savings to the nation. We estimate net benefits of \$6 to \$38 billion per year in 2010. Such net benefits, not generally observed in macroeconomic models requiring structural change in the economy to accommodate reductions in carbon emissions, result from the application of cost-saving energy technologies at the sectoral level.

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 cost-effective 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.

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.

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 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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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.

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 lead to further carbon reductions over the next quarter century. As such, this report underscores the value of energy technology research, development, demonstration, and diffusion as a public response to global climate change.

Two overarching conclusions emerge from the analysis of alternative carbon scenarios. First, a vigorous national commitment to develop and deploy cost-effective energy-efficient and low-carbon technologies, along with utility sector investments, 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). It must be noted that such a vigorous national commitment would have to go far beyond current efforts.

Second, 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-effective by the year 2020, assuming a vigorous and sustained program of energy R&D beginning now and extending beyond 2010.

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 lead to 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 and to modify 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.

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" (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-efficient technology.

The other two cases, dubbed the "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. These two 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. They 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 some sectors (buildings and industry), the carbon price signal, combined with policies promoting energy efficiency, is believed to trigger the bulk of the additional carbon reductions portrayed in the HE/LC cases. 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.

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. 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, as well.

The HE/LC scenario with \$50/tonne carbon charge has the potential to reduce carbon emissions by approximately 380 million tonnes, thereby achieving 1990 carbon emission levels in 2010. Of this 380 million tonne reduction, about 190 million tonnes are from supply technologies. The largest of these technologies involves increased use of natural gas for electricity generation (including repowering existing coal-fired power plants and dispatching natural gas-fired power plants in preference to coal plants). Other electricity-supply technologies include renewables (wind, co-firing coal-based power plants with biofuels, expansion of hydropower capacity, mixing ethanol fuel with gasoline), power plant efficiency improvements, and nuclear power plant extensions. The remaining 40 million tonnes comes from deploying other low-carbon technologies. The largest of these – deploying advanced combustion turbines in industry – also involves increased use of natural gas. Other technologies in this category include fuel cell cogenerators in large industrial buildings, ethanol from cellulose, biomass and black liquor gasification, and low carbon industrial process technologies. Figure 1.3 (below) illustrates this breakout of carbon emissions reductions by type of technology.

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 240 million tonnes (as forecast in the BAU case) to 120. The HE/LC scenario with \$50/tonne carbon charge reduces carbon emissions in 2010 by about 130 million tonnes (compared with the 1997 level).

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 the three scenarios for 2010. (We have included only the high-efficiency/low-carbon case at \$50/tonne in the table and figure for simplicity.) In addition, the 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

	1990	1997	2010		
			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 \$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.

Figure 1.1 Primary Energy Use in Quads: 1990-2010

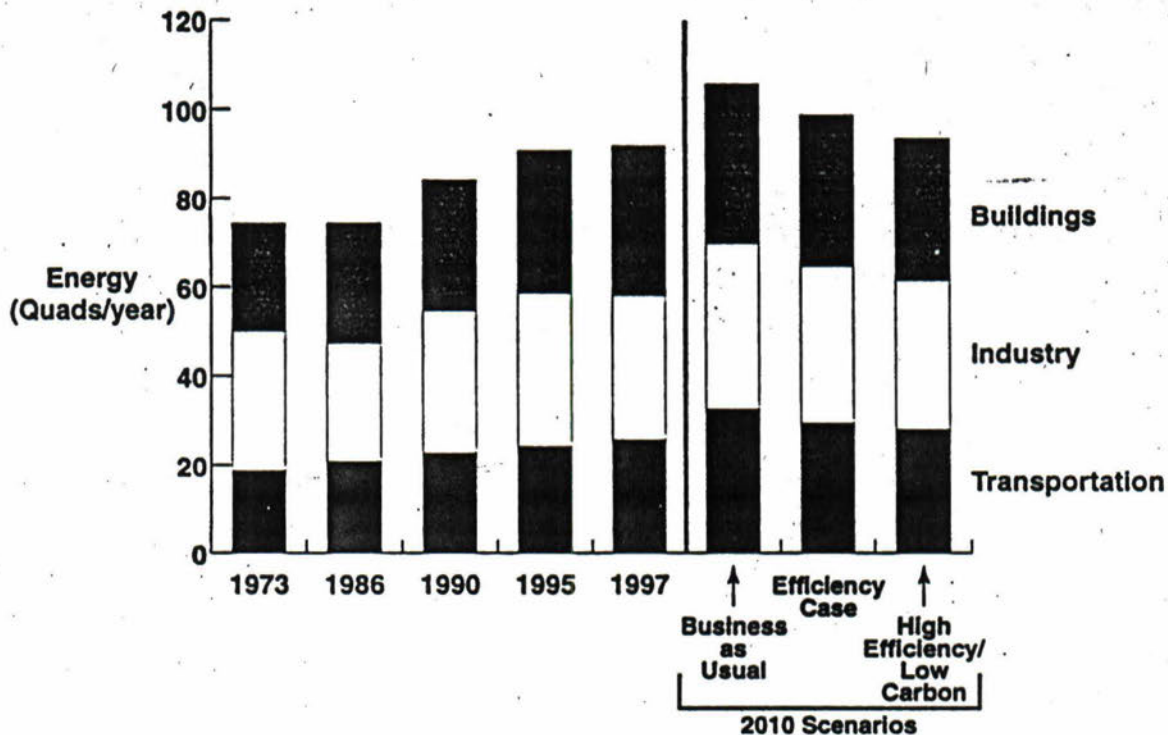


Table 1.2 documents the impact of these projected energy savings in 2010 on carbon emissions in that same year. It also presents the results of the HE/LC scenarios with both \$25 and \$50 per tonne carbon charges. These scenarios show significant carbon reductions from the combination of greater efficiency improvements and increased use of advanced low-carbon technologies.² 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.

Table 1.2 Carbon Emissions (MtC): 1990-2010

	1990	1997	2010			
			Business-as-Usual (BAU) Case	Efficiency Case	High-Efficiency/Low-Carbon ^a	
					\$25/tonne	\$50/tonne
Buildings	460	511	571	546	527	509
Industry	452	482	534	512	488	452
Transportation	432	486	616	543	528	513
Utilities ^b	-	-	-	-	-48	-136
Total (rounded)	1340	1480	1720	1600	1490	1340
Change from 1990		140	380	260	150	0
Change from BAU	-	-	-	-120	-230	-380

^aThis 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.

^bThe entries in the last two columns are negative as they correspond to reductions in carbon emissions resulting from the increased use of natural gas in power plants as a result of the \$50/tonne carbon permit price in this scenario.

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 380 million tonnes.
- The energy-efficiency gains incorporated in the efficiency case cut overall growth between 1990 and 2010 by one-third (from 380 to 260 million tonnes). This represents a carbon increase of 19% 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 (carbon-based dispatching and repowering) contribute nearly 35 million tonnes, and other low-carbon technology, particularly renewables and advanced turbine systems, produce approximately another 25 million tonnes.
- The HE/LC scenario with \$50/tonne carbon charge has the potential to reduce carbon emissions by approximately 380 million tonnes, thereby achieving 1990 carbon emission levels in 2010. Of this 380 million tonne carbon reduction, about 190 million tonnes are from increased energy efficiency, 140 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.

100 million of the 140 million tonnes of carbon reductions in the utility sector comes from redispatching the utility system (favoring the use of low-carbon fuels) and from repowering coal plants with natural gas. Both are cost-effective with a \$50/tonne carbon charge. The remaining 40 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 remaining 50 million tonnes of carbon reductions in industry and transportation are about equally divided among three sets of fuels/technologies: (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 240 million tonnes (as forecast in the BAU case) to 120. The HE/LC scenario with \$50/tonne carbon charge *reduces* carbon emissions in 2010 by about 130 million tonnes (compared with the 1997 level).

Figure 1.2 Reductions in Carbon Emissions from Each Scenario

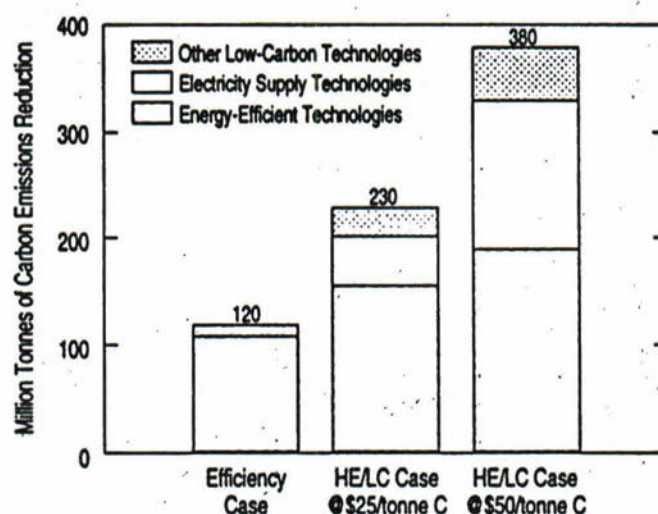


Figure 1.3 Reductions in Carbon Emissions from Each Type of Technology

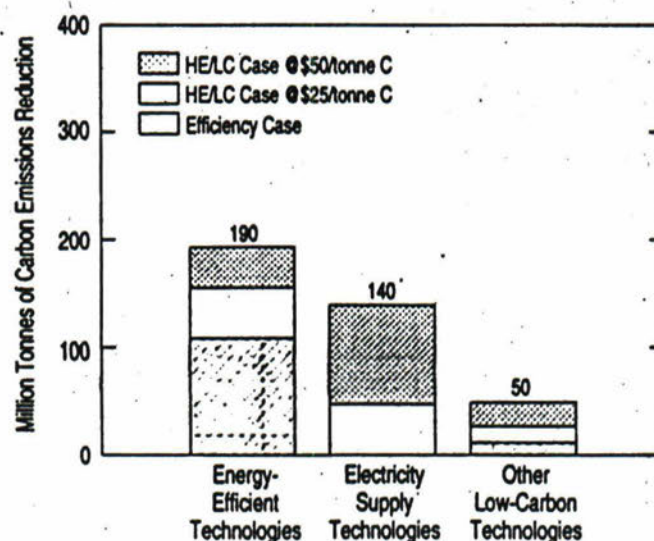


Table 1.3 provides a comparison of the growth rate in energy and in carbon emissions for the four cases, from 1990 to 2010. For the BAU and efficiency cases, the growth in carbon emissions is slightly more rapid than the increase in energy demand. For the HE/LC cases, carbon emissions decline while energy 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.

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	1.16%	0.60%	0.05%	-0.76%
Energy Consumption Per GDP (E/GDP)	-0.77%	-1.30%	-1.51%	-1.71%
Carbon Emissions Per GDP (C/GDP) ^b	-0.70%	-1.25%	-1.79%	-2.59%

^a The Gross Domestic Product in 1995 was \$6,739 billion chained 1992 dollars.

^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.

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.

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 beyond 2010 is beyond the scope of this report.

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, while 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 are forecast to 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, controls and communications; 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 after 2010 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; ultra-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 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 AND SOURCES OF CARBON REDUCTIONS

The business-as-usual scenario projects an increase of 380 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 \$25 and \$50/tonne C for the two cases considered, 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 HE/LC case, there is a potential to roughly return to 1990 levels of carbon emissions in 2010 at a cost of approximately \$50/tonne carbon. About two-thirds of the increase in carbon emissions is eliminated in the case with \$25/tonne carbon charge.

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 significantly greater role by 2010 are omitted from Table 1.4; these resources include include photovoltaics, geothermal, solar thermal, and landfill gas.

It is important to recognize that there are significant uncertainties in the analysis and in many of the factors that will determine the feasibility and the costs of achieving the carbon reductions shown in Table 1.4. We present below a summary of 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 policies or programs to achieve market acceptance.

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

	Efficiency Case	High-Efficiency/Low-Carbon Case	
		\$25/tonne	\$50/tonne*
Buildings			
Energy efficiency	25	42	59
Fuel cells		2	3
	25	44	62
Industry			
Energy efficiency	22	36	51
Advanced turbine systems		5	17 (15-26)
Biomass and black liquor gasification, cement clinker replacement, and aluminum technologies		5	14 (13-16)
	22	46	82
Transportation			
Energy efficiency	61	74	87
Ethanol	12	14	16
	73	88	103
Utility Supply Options			
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 (rounded)	120	226	383

*Numbers in parenthesis are ranges, as documented in the text of the report.

We have analyzed the economics of carbon emissions reductions from two different perspectives. In the first, which we label "best estimate," we evaluate all costs and 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 cost, for buildings, is based on the fact that the money for residential buildings is derived from home mortgages or home improvement loans. The higher cost 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. One could argue that a lower discount rate should be used for the "best estimate" case – namely, a social discount rate which might be between 3 and 7% real – but we have made a more conservative assumption on discount rates. For the "best estimate" 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 little direct program costs. 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.

The second perspective, which we label "alternative view," 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 15% of the cost of efficiency measures. Other data and assumptions in this case are the same as for the "best estimate" case.

The results of the economic analysis are presented in Table 1.5. We show results for two of our scenarios (efficiency case and HE/LC at \$50/tonne carbon) and for both the "best estimate" and "alternative view" perspectives. Also, we have grouped the results into just four categories of energy technologies. For more detail, both on the results and methodology, the reader is referred to Appendix A-2.

The "best estimate" for the efficiency scenario shows annual net benefits of \$26 billion in 2010 (\$26 billion in costs and \$52 billion in benefits). This value reflects the fact that, even after accounting for energy-efficiency investment, the annual energy savings (without including the benefits of reduced carbon emissions) are \$26 billion greater than the required investment. The "best estimate" for the HE/LC scenario with \$50/tonne carbon charge produces an annual net benefit of \$38 billion in 2010 (\$50 billion in costs and \$87 billion in benefits).

The "alternative view" shows annual net direct benefits for the efficiency scenario of \$7 billion in 2010 (\$45 billion in costs and \$52 billion in benefits). For the HE/LC (\$50/tonne carbon) scenario, the "alternative view" indicates annual net benefits of \$6 billion in 2010 (\$81 billion in costs and \$87 billion in benefits).

Table 1.5 Costs and Benefits of the Efficiency and High-Efficiency/Low-Carbon Scenarios : Best Case and Alternative View Estimates (billions of 1995\$, annualized)

	Efficiency Case		High-Efficiency/Low-Carbon Case ^b	
	Net Benefits ^c (billion 1995\$)	Carbon Savings MtC	Net Benefits ^c (billion 1995\$)	Carbon Savings MtC
Best Estimate				
Energy Efficiency ^a	26	120	43	213
Electricity Dispatch	0	0	(1.8)	55
Electricity Repowering	0	0	(1.8)	45
Other Low-Carbon Technologies	0	0	(1.6)	72
Total	26	120	38	385
Alternative View				
Energy Efficiency ^a	7	120	12.5	213
Electricity Dispatch	0	0	(2.8)	55
Electricity Repowering	0	0	(1.9)	45
Other Low-Carbon Technologies	0	0	(1.8)	72
Total	7	120	6	385

^a Energy efficiency category includes ethanol in transportation.

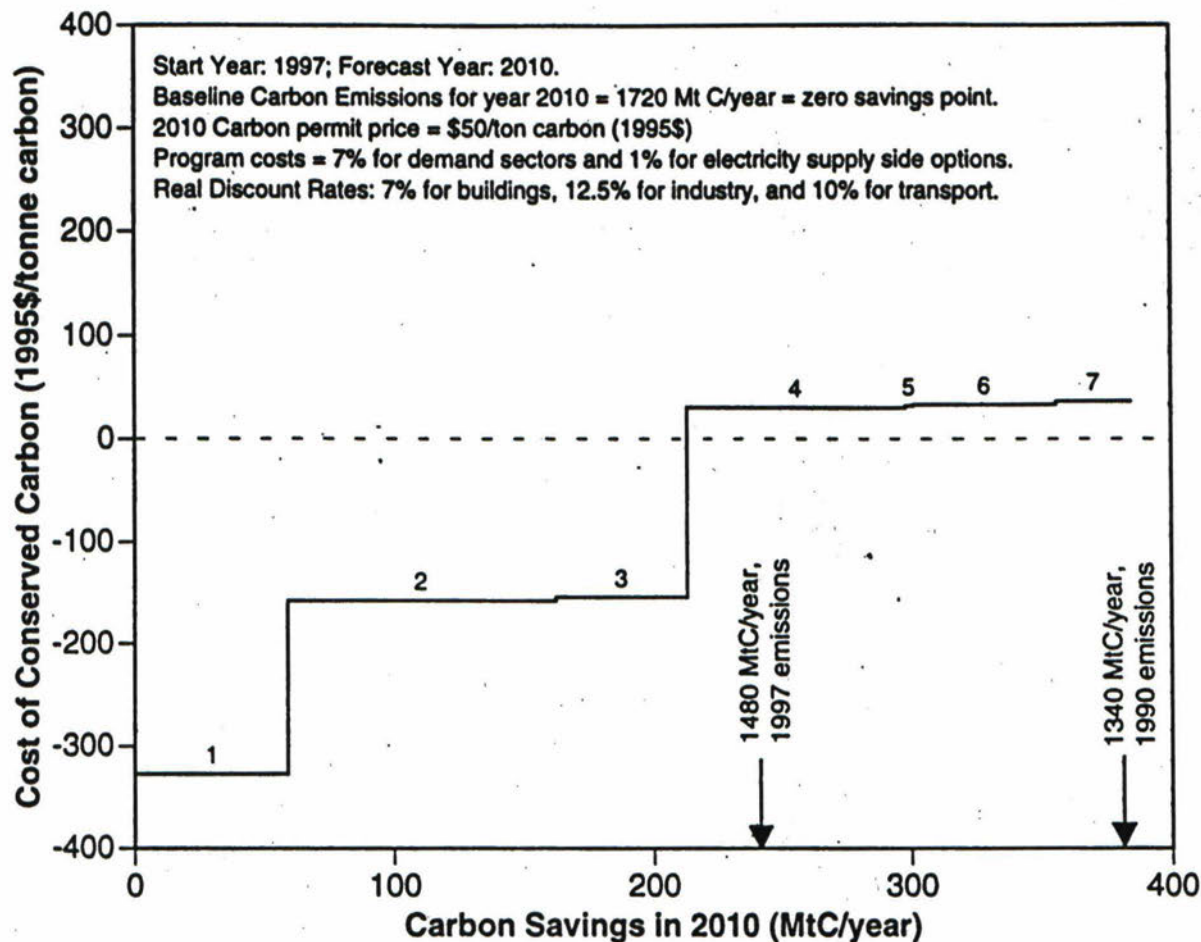
^b Benefits and carbon savings in the HE/LC case are relative to BAU case.

^c Net benefits are calculated as annual energy savings minus annualized capital costs (energy savings equal zero for supply-side technologies and advanced low-carbon technologies).

Another way to present these results is in the form of a conservation supply curve, as shown for the HE/LC scenario in Figure 1.4. This figure has the cost of conserved carbon on the y-axis (1995\$/tonne C) and carbon savings in 2010 (MtC/year) on the x-axis. Carbon savings from buildings sector efficiency are least expensive, followed by industrial and transport sector efficiency. All three of these sectors reduce carbon emissions and save money at the same time. More than 200 MtC of carbon reductions can be achieved in these three sectors. The remaining 180 MtC of carbon reductions in 2010 are in electricity supply side and advanced carbon saving options. These savings are achieved at a cost of \$30-37/tonne C, but the added cost of these options is more than outweighed by the benefits captured by the money-saving options, resulting in the net benefit of \$38 billion per year.

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 *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: (1) increase in gas demand because of the large-scale substitution of natural gas for coal, (2) 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 (3) 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 will reduce the cost of natural gas, a benefit that we have not included in Table 1.5.

Figure 1.4 Cost of Carbon Savings in 2010, High Efficiency/Low Carbon Case (Best Estimate)



	Annual Savings		Annual Costs
1. Buildings Efficiency	\$19.3B	4. Electric Repowering/Other	\$2.6B
2. Transport Efficiency	\$16.2B	5. Fuel Cells in Commercial Bldgs.	\$0.1B
3. Industry Efficiency	\$7.9B	6. Electricity Dispatch	\$1.8B
		7. Industry Other	\$1.1B
Total Savings	\$43.4B	Total Costs	\$5.6B

Total Annual Net Savings (Items 1 through 7) = \$38 B/year

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 annual revenues of \$65 billion.

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 – are favorable: from \$6 billion to \$38 billion per year in 2010.

This analysis counts the benefits of reduced expenditures on energy but does not explicitly value the benefits of reducing carbon dioxide emissions.

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, presumably in response to an international agreement on climate change or other events that result in a national determination to reduce the growth of carbon emissions. In the high-efficiency/low-carbon case, we assume a vigorous national program of research, development, demonstration, and diffusion, and a trading regime for carbon with a domestic permit price of \$50/tonne carbon. Without some scheme that provides an incentive of this nature for switching from coal to natural gas, and for deploying other low-carbon technologies, much of the carbon reductions in our case would not be possible.

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 technology 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 the cost-effective technology can be deployed to achieve major reductions in carbon emissions by 2010. Cost-effective energy efficiency alone can take the nation 30 to 50% of the way to 1990 levels (from our expected base case results). An important finding is that 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.³ Finally, we identify additional technologies that can contribute up to 20% of the 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.

REFERENCES

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 \$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.

³ 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-efficiency 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 water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), ozone (O_3), nitrous oxide (N_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. 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 technologies reduce CO_2 emissions by displacing the need for fossil fuel combustion; this report focuses on this single greenhouse gas. This report quantifies the climate benefits of energy-efficient and low-carbon technologies 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 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 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 stabilizing carbon emissions by 2010 at their 1990 level, which is one possible national target under discussion.

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 "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. They 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. They 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 some sectors (buildings and industry), the carbon price signal, combined with policies promoting energy efficiency, is believed to trigger the bulk of the additional carbon reductions portrayed in the HE/LC cases. 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 reported as base years against which we 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 1998 are needed to achieve our 2010 scenarios.

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 reductions 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 growth in residential and commercial 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 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 in the industrial, electricity, and transportation sectors increase throughout the forecast period; natural gas prices for the residential and commercial sectors decrease significantly. 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 these 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 remove or reduce market failures which inhibit the use of energy-efficient and low-carbon systems. 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.

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 the role of R&D on energy-efficient and low-carbon technologies as a means to deal with climate change and other environmental impacts has been inadequately recognized. 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 CO₂ emissions from power plants. It also assesses the impact of a \$25/tonne and \$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 cofiring coal with biomass, 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

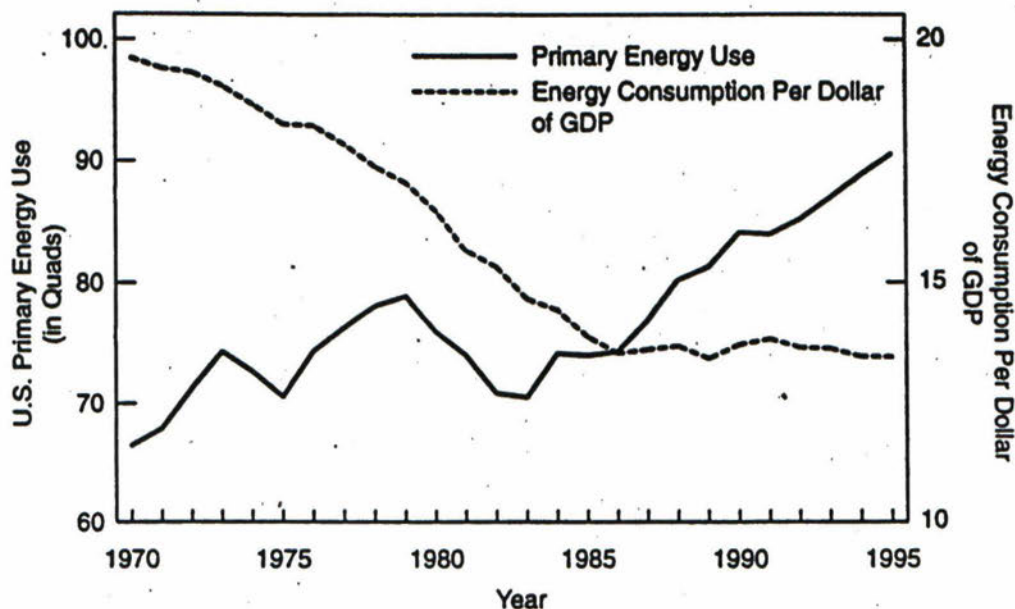
In studying historical trends in energy use and carbon emissions, we have chosen to highlight the years 1973, the beginning of rising energy prices to the nation; 1986, the year in which energy prices began a ten-year decline in real terms; 1990, the year generally used as a reference for carbon emissions; 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 \$100 billion per year on R&D, dwarfing the government expenditure on all non-defense technology R&D. Of this 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.

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).

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 2.3 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%).

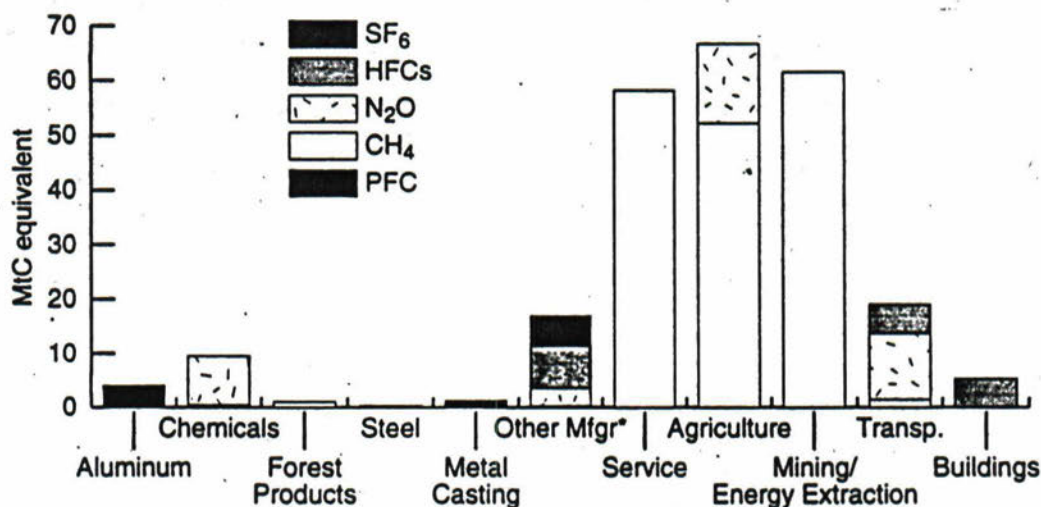
Table 2.4 Carbon Emissions from Fossil Energy Consumption: 1973 to 1997

	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-CO₂ 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 hexafluoride (SF₆). 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-CO₂ greenhouse gas contribution is from methane (CH₄), which is responsible for 177.5 MtC equivalent and has a GWP of 21. Next is nitrous oxide (N₂O), 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. SF₆ 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-CO₂ Greenhouse Gas Emissions by End-Use Sector and Industry



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).

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 (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-E 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, 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 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 public health benefits that have resulted from advances in energy-efficient and renewable energy technologies, and Romm (1994) describes productivity gains that have accompanied investments in industrial efficiency improvements.

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”, paper to be presented at the Thirty-Second Annual Intersociety Energy Conversion Engineering Congress, Honolulu, HI, July 27-August 1.

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

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

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

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

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

Domestic Odd's Copy
~~Report~~
Studies

Proposed Media Roll Out for Five Laboratory Climate Change Study

THE NEWS

Peer-reviewed study demonstrates ability of U.S. industry to meet range of possible climate change commitments through development and deployment of technologies that increase efficiency and reduce emissions. The study's conclusions are clear: Clean energy technology can prevent climate change and contribute to economic growth. Industry can remain strong and competitive -- even with the challenges of reducing global pollution.

To illustrate study results -- and demonstrate that the technology solution is viable -- DOE has a set of additional, newsworthy announcements. For example:

- Clean diesel grant to Caterpillar and Cummins, reducing exhaust fumes
- Air conditioning standards for low-cost cooling -- less electricity means reduced emissions from power plants
- Climate technology grants to communities
- A call for proposals to develop technologies that recycle or isolate greenhouse gases, such as carbon emissions released by power plants.
- As many as 10 of DOE's 36 R&D 100 awards are technologies that contribute to reducing global warming. For example, Lawrence Berkely Laboratory's innovation reduces costs for applying energy efficient film on building windows.

ANNOUNCEMENT OPTIONS

1. Event or announcement by the Vice President with Secretary Peña

- DOE issues press release
- 2. New York Times exclusive on study only; broader announcement via press release*
 - Include presidential/vice presidential quote in release
 - Media conference call with Secretary Peña and WH principals
 - Follow up media by DOE, CEQ

3. New York Times exclusive on study only; broader announcement via Secretarial event

- President's quote in release
- Follow up media by DOE, CEQ
- Delay until September

FOLLOW UP MEDIA

Opinion editorial: Secretary Peña's byline

Editorial boards: Provide top 25 papers with release and studies...Calls by DOE/CEQ to Washington Post, New York Times...Mailings to Business Week, Automotive Week...

Columnists: Robert Samuelson...(add'l TBD)

Broadcast: Seek opportunities to discuss study on CNBC programs, Talk of the Nation (weekly or Friday science show), Diane Rehm, TechnoPolitics, etc.

Regional: Participating laboratories promote to regional media (New Mexico, Chicago, Tennessee, Denver, Washington State) -- via statements by lab directors, mailings/calls to editorial boards

SCENARIOS OF U.S. CARBON REDUCTIONS

Potential Impacts of Energy-Efficient and Low-Carbon 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

Operated by Battelle for the
U.S. Department of Energy

Pacific Northwest
National Laboratory



National Renewable
Energy Laboratory



Arizona National
Laboratory

DRAFT - August 1, 1997

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

*Coordinating laboratories for this study

SCENARIOS OF U.S. CARBON REDUCTIONS

Potential Impacts of Energy-Efficient and Low-Carbon Technologies by 2010 and Beyond

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

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Prepared for
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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 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 research, development, and deployment of clean technologies. Current projections suggest that a carbon emissions reduction of 380 million metric tons (MtC) 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 cost-effective 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 alone can reduce carbon emissions by 120 MtC by 2010. Under more aggressive assumptions motivated in part by a \$25/tonne carbon permit price, a combination of energy-efficient and low-carbon technologies can reduce 2010 emissions by a total of 230 MtC. Under a \$50/tonne carbon permit price, technology investments reduce 2010 emissions by about 380 MtC. 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 380 MtC/year by 2010) can produce benefits that exceed costs, counting as benefits only the energy savings to the nation. We estimate net benefits of \$6 to \$38 billion per year in 2010. Such net benefits, not generally observed in macroeconomic models requiring structural change in the economy to accommodate reductions in carbon emissions, result from the application of cost-saving energy technologies at the sectoral level.

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 cost-effective 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.

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.

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.

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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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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 lead to further carbon reductions over the next quarter century. As such, this report underscores the value of energy technology research, development, demonstration, and diffusion as a public response to global climate change.

Two overarching conclusions emerge from the analysis of alternative carbon scenarios. First, a vigorous national commitment to develop and deploy cost-effective energy-efficient and low-carbon technologies, along with utility sector investments, 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). It must be noted that such a vigorous national commitment would have to go far beyond current efforts.

Second, 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-effective by the year 2020, assuming a vigorous and sustained program of energy R&D beginning now and extending beyond 2010.

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 lead to 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 and to modify 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.

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" (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-efficient technology.

The other two cases, dubbed the "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. These two 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. They 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 some sectors (buildings and industry), the carbon price signal, combined with policies promoting energy efficiency, is believed to trigger the bulk of the additional carbon reductions portrayed in the HE/LC cases. 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.

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. 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, as well.

The HE/LC scenario with \$50/tonne carbon charge has the potential to reduce carbon emissions by approximately 380 million tonnes, thereby achieving 1990 carbon emission levels in 2010. Of this 380 million tonne reduction, about 190 million tonnes are from supply technologies. The largest of these technologies involves increased use of natural gas for electricity generation (including repowering existing coal-fired power plants and dispatching natural gas-fired power plants in preference to coal plants). Other electricity-supply technologies include renewables (wind, co-firing coal-based power plants with biofuels, expansion of hydropower capacity, mixing ethanol fuel with gasoline), power plant efficiency improvements, and nuclear power plant extensions. The remaining 40 million tonnes comes from deploying other low-carbon technologies. The largest of these – deploying advanced combustion turbines in industry – also involves increased use of natural gas. Other technologies in this category include fuel cell cogenerators in large industrial buildings, ethanol from cellulose, biomass and black liquor gasification, and low carbon industrial process technologies. Figure 1.3 (below) illustrates this breakout of carbon emissions reductions by type of technology.

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 240 million tonnes (as forecast in the BAU case) to 120. The HE/LC scenario with \$50/tonne carbon charge reduces carbon emissions in 2010 by about 130 million tonnes (compared with the 1997 level).

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 the three scenarios for 2010. (We have included only the high-efficiency/low-carbon case at \$50/tonne in the table and figure for simplicity.) In addition, the 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

	1990	1997	2010		
			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 \$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.

Figure 1.1 Primary Energy Use in Quads: 1990-2010

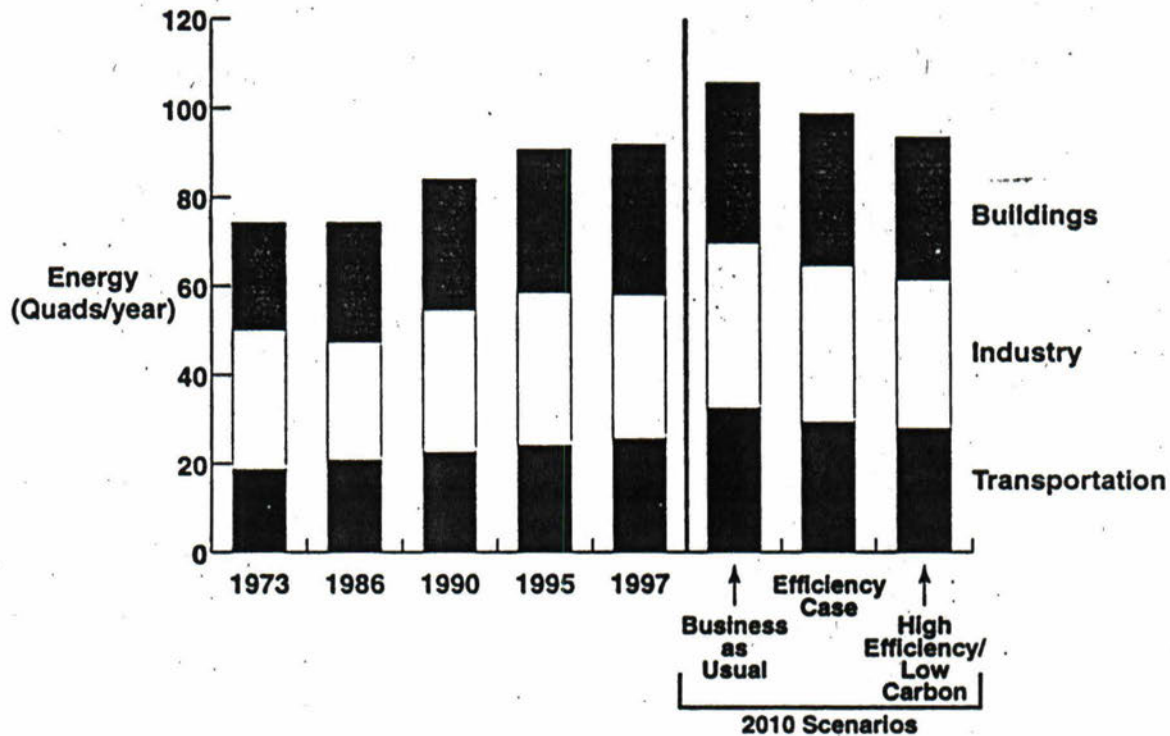


Table 1.2 documents the impact of these projected energy savings in 2010 on carbon emissions in that same year. It also presents the results of the HE/LC scenarios with both \$25 and \$50 per tonne carbon charges. These scenarios show significant carbon reductions from the combination of greater efficiency improvements and increased use of advanced low-carbon technologies.² 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.

Table 1.2 Carbon Emissions (MtC): 1990-2010

	1990	1997	2010			
			Business-as-Usual (BAU) Case	Efficiency Case	High-Efficiency/Low-Carbon ^a	
					\$25/tonne	\$50/tonne
Buildings	460	511	571	546	527	509
Industry	452	482	534	512	488	452
Transportation	432	486	616	543	528	513
Utilities ^b	-	-	-	-	-48	-136
Total (rounded)	1340	1480	1720	1600	1490	1340
Change from 1990		140	380	260	150	0
Change from BAU	-	-	-	-120	-230	-380

^aThis 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.

^bThe entries in the last two columns are negative as they correspond to reductions in carbon emissions resulting from the increased use of natural gas in power plants as a result of the \$50/tonne carbon permit price in this scenario.

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 380 million tonnes.
- The energy-efficiency gains incorporated in the efficiency case cut overall growth between 1990 and 2010 by one-third (from 380 to 260 million tonnes). This represents a carbon increase of 19% 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 (carbon-based dispatching and repowering) contribute nearly 35 million tonnes, and other low-carbon technology, particularly renewables and advanced turbine systems, produce approximately another 25 million tonnes.
- The HE/LC scenario with \$50/tonne carbon charge has the potential to reduce carbon emissions by approximately 380 million tonnes, thereby achieving 1990 carbon emission levels in 2010. Of this 380 million tonne carbon reduction, about 190 million tonnes are from increased energy efficiency, 140 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.

100 million of the 140 million tonnes of carbon reductions in the utility sector comes from redispatching the utility system (favoring the use of low-carbon fuels) and from repowering coal plants with natural gas. Both are cost-effective with a \$50/tonne carbon charge. The remaining 40 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 remaining 50 million tonnes of carbon reductions in industry and transportation are about equally divided among three sets of fuels/technologies: (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 240 million tonnes (as forecast in the BAU case) to 120. The HE/LC scenario with \$50/tonne carbon charge *reduces* carbon emissions in 2010 by about 130 million tonnes (compared with the 1997 level).

Figure 1.2 Reductions in Carbon Emissions from Each Scenario

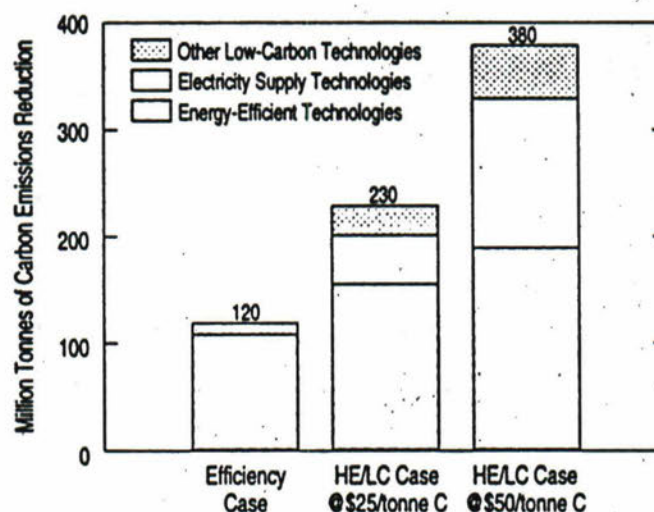


Figure 1.3 Reductions in Carbon Emissions from Each Type of Technology

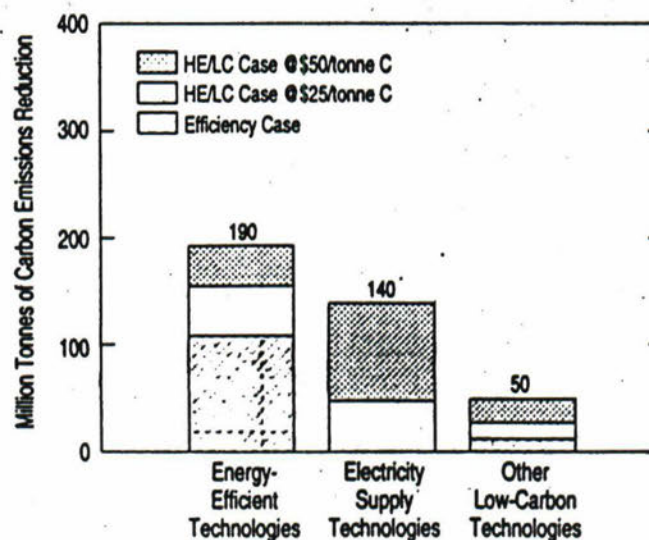


Table 1.3 provides a comparison of the growth rate in energy and in carbon emissions for the four cases, from 1990 to 2010. For the BAU and efficiency cases, the growth in carbon emissions is slightly more rapid than the increase in energy demand. For the HE/LC cases, carbon emissions decline while energy 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.

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	1.16%	0.60%	0.05%	-0.76%
Energy Consumption Per GDP (E/GDP)	-0.77%	-1.30%	-1.51%	-1.71%
Carbon Emissions Per GDP (C/GDP) ^b	-0.70%	-1.25%	-1.79%	-2.59%

^a The Gross Domestic Product in 1995 was \$6,739 billion chained 1992 dollars.

^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.

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.

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 beyond 2010 is beyond the scope of this report.

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, while 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 are forecast to 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, controls and communications; 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 after 2010 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; ultra-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 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 AND SOURCES OF CARBON REDUCTIONS

The business-as-usual scenario projects an increase of 380 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 \$25 and \$50/tonne C for the two cases considered, 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 HE/LC case, there is a potential to roughly return to 1990 levels of carbon emissions in 2010 at a cost of approximately \$50/tonne carbon. About two-thirds of the increase in carbon emissions is eliminated in the case with \$25/tonne carbon charge.

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 significantly greater role by 2010 are omitted from Table 1.4; these resources include photovoltaics, geothermal, solar thermal, and landfill gas.

It is important to recognize that there are significant uncertainties in the analysis and in many of the factors that will determine the feasibility and the costs of achieving the carbon reductions shown in Table 1.4. We present below a summary of 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 policies or programs to achieve market acceptance.

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

	Efficiency Case	High-Efficiency/Low-Carbon Case	
		\$25/tonne	\$50/tonne*
Buildings			
Energy efficiency	25	42	59
Fuel cells		2	3
	25	44	62
Industry			
Energy efficiency	22	36	51
Advanced turbine systems		5	17 (15-26)
Biomass and black liquor gasification, cement clinker replacement, and aluminum technologies		5	14 (13-16)
	22	46	82
Transportation			
Energy efficiency	61	74	87
Ethanol	12	14	16
	73	88	103
Utility Supply Options			
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 (rounded)	120	226	383

* Numbers in parenthesis are ranges, as documented in the text of the report.

We have analyzed the economics of carbon emissions reductions from two different perspectives. In the first, which we label "best estimate," we evaluate all costs and 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 cost, for buildings, is based on the fact that the money for residential buildings is derived from home mortgages or home improvement loans. The higher cost 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. One could argue that a lower discount rate should be used for the "best estimate" case – namely, a social discount rate which might be between 3 and 7% real – but we have made a more conservative assumption on discount rates. For the "best estimate" 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 little direct program costs. 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.

The second perspective, which we label "alternative view," 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 15% of the cost of efficiency measures. Other data and assumptions in this case are the same as for the "best estimate" case.

The results of the economic analysis are presented in Table 1.5. We show results for two of our scenarios (efficiency case and HE/LC at \$50/tonne carbon) and for both the "best estimate" and "alternative view" perspectives. Also, we have grouped the results into just four categories of energy technologies. For more detail, both on the results and methodology, the reader is referred to Appendix A-2.

The "best estimate" for the efficiency scenario shows annual net benefits of \$26 billion in 2010 (\$26 billion in costs and \$52 billion in benefits). This value reflects the fact that, even after accounting for energy-efficiency investment, the annual energy savings (without including the benefits of reduced carbon emissions) are \$26 billion greater than the required investment. The "best estimate" for the HE/LC scenario with \$50/tonne carbon charge produces an annual net benefit of \$38 billion in 2010 (\$50 billion in costs and \$87 billion in benefits).

The "alternative view" shows annual net direct benefits for the efficiency scenario of \$7 billion in 2010 (\$45 billion in costs and \$52 billion in benefits). For the HE/LC (\$50/tonne carbon) scenario, the "alternative view" indicates annual net benefits of \$6 billion in 2010 (\$81 billion in costs and \$87 billion in benefits).

Table 1.5 Costs and Benefits of the Efficiency and High-Efficiency/Low-Carbon Scenarios : Best Case and Alternative View Estimates (billions of 1995\$, annualized)

	Efficiency Case		High-Efficiency/Low-Carbon Case ^b	
	Net Benefits ^c (billion 1995\$)	Carbon Savings MtC	Net Benefits ^c (billion 1995\$)	Carbon Savings MtC
Best Estimate				
Energy Efficiency ^a	26	120	43	213
Electricity Dispatch	0	0	(1.8)	55
Electricity Repowering	0	0	(1.8)	45
Other Low-Carbon Technologies	0	0	(1.6)	72
Total	26	120	38	385
Alternative View				
Energy Efficiency ^a	7	120	12.5	213
Electricity Dispatch	0	0	(2.8)	55
Electricity Repowering	0	0	(1.9)	45
Other Low-Carbon Technologies	0	0	(1.8)	72
Total	7	120	6	385

^a Energy efficiency category includes ethanol in transportation.

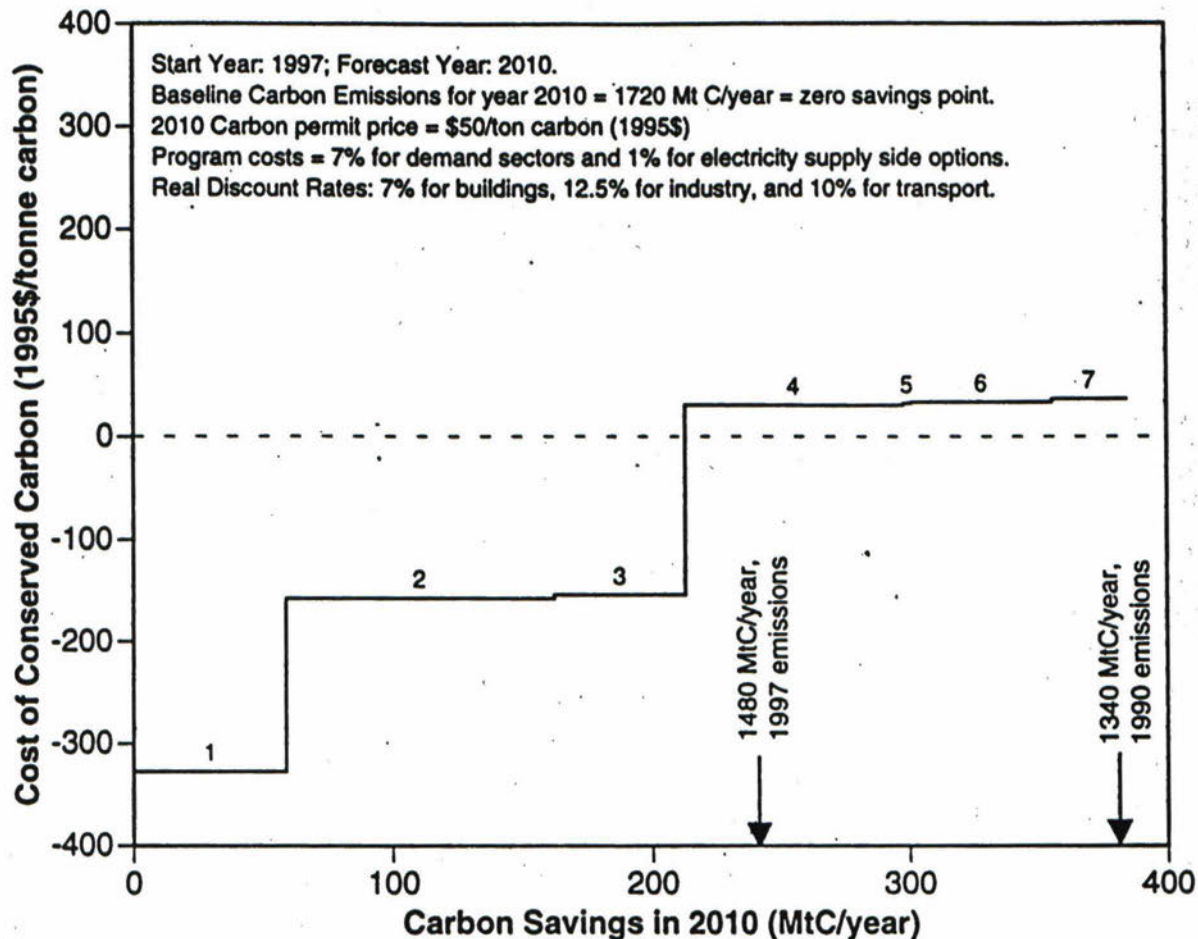
^b Benefits and carbon savings in the HE/LC case are relative to BAU case.

^c Net benefits are calculated as annual energy savings minus annualized capital costs (energy savings equal zero for supply-side technologies and advanced low-carbon technologies).

Another way to present these results is in the form of a conservation supply curve, as shown for the HE/LC scenario in Figure 1.4. This figure has the cost of conserved carbon on the y-axis (1995\$/tonne C) and carbon savings in 2010 (MtC/year) on the x-axis. Carbon savings from buildings sector efficiency are least expensive, followed by industrial and transport sector efficiency. All three of these sectors reduce carbon emissions and save money at the same time. More than 200 MtC of carbon reductions can be achieved in these three sectors. The remaining 180 MtC of carbon reductions in 2010 are in electricity supply side and advanced carbon saving options. These savings are achieved at a cost of \$30-37/tonne C, but the added cost of these options is more than outweighed by the benefits captured by the money-saving options, resulting in the net benefit of \$38 billion per year.

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 *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: (1) increase in gas demand because of the large-scale substitution of natural gas for coal, (2) 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 (3) 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 will reduce the cost of natural gas, a benefit that we have not included in Table 1.5.

Figure 1.4 Cost of Carbon Savings in 2010, High Efficiency/Low Carbon Case (Best Estimate)



	Annual Savings		Annual Costs
1. Buildings Efficiency	\$19.3B	4. Electric Repowering/Other	\$2.6B
2. Transport Efficiency	\$16.2B	5. Fuel Cells in Commercial Bldgs.	\$0.1B
3. Industry Efficiency	\$7.9B	6. Electricity Dispatch	\$1.8B
		7. Industry Other	\$1.1B
Total Savings	\$43.4B	Total Costs	\$5.6B

Total Annual Net Savings (Items 1 through 7) = \$38 B/year

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 annual revenues of \$65 billion.

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 – are favorable: from \$6 billion to \$38 billion per year in 2010.

This analysis counts the benefits of reduced expenditures on energy but does not explicitly value the benefits of reducing carbon dioxide emissions.

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, presumably in response to an international agreement on climate change or other events that result in a national determination to reduce the growth of carbon emissions. In the high-efficiency/low-carbon case, we assume a vigorous national program of research, development, demonstration, and diffusion, and a trading regime for carbon with a domestic permit price of \$50/tonne carbon. Without some scheme that provides an incentive of this nature for switching from coal to natural gas, and for deploying other low-carbon technologies, much of the carbon reductions in our case would not be possible.

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 technology 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 the cost-effective technology can be deployed to achieve major reductions in carbon emissions by 2010. Cost-effective energy efficiency alone can take the nation 30 to 50% of the way to 1990 levels (from our expected base case results). An important finding is that 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.³ Finally, we identify additional technologies that can contribute up to 20% of the 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.

REFERENCES

- 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 \$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.

³ 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-efficiency 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 water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), ozone (O_3), nitrous oxide (N_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. 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 technologies reduce CO_2 emissions by displacing the need for fossil fuel combustion; this report focuses on this single greenhouse gas. This report quantifies the climate benefits of energy-efficient and low-carbon technologies 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 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 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 stabilizing carbon emissions by 2010 at their 1990 level, which is one possible national target under discussion.

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 "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. They 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. They include a focused national R&D effort to develop and transform markets for low-carbon energy options (e.g., fuel cells for microgeneration 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 some sectors (buildings and industry), the carbon price signal, combined with policies promoting energy efficiency, is believed to trigger the bulk of the additional carbon reductions portrayed in the HE/LC cases. 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 reported as base years against which we 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 1998 are needed to achieve our 2010 scenarios.

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 reductions 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 growth in residential and commercial 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 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 in the industrial, electricity, and transportation sectors increase throughout the forecast period; natural gas prices for the residential and commercial sectors decrease significantly. 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 these 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 remove or reduce market failures which inhibit the use of energy-efficient and low-carbon systems. 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.

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 the role of R&D on energy-efficient and low-carbon technologies as a means to deal with climate change and other environmental impacts has been inadequately recognized. 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 CO₂ emissions from power plants. It also assesses the impact of a \$25/tonne and \$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 cofiring coal with biomass, 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

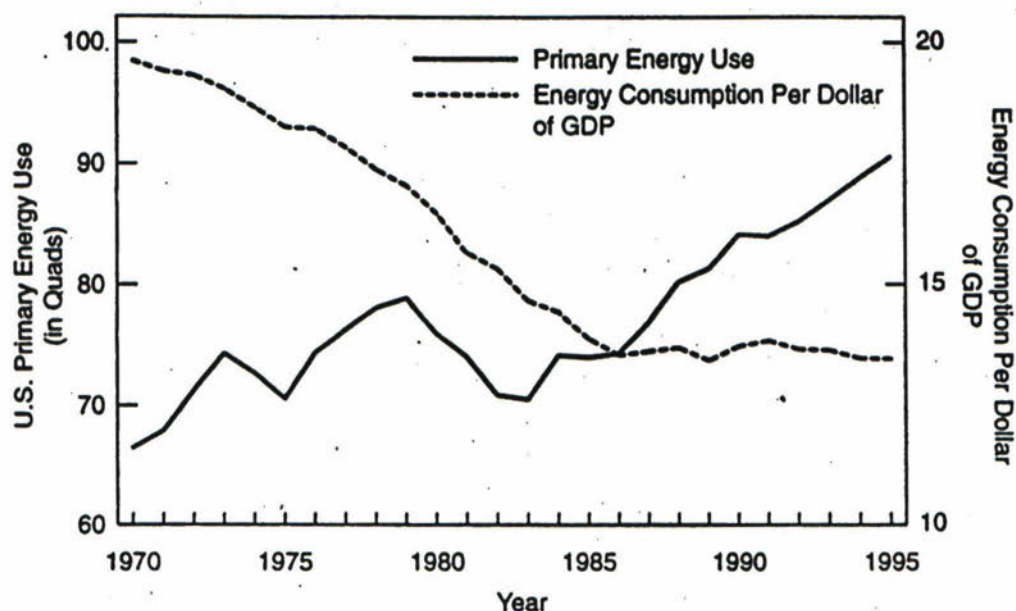
In studying historical trends in energy use and carbon emissions, we have chosen to highlight the years 1973, the beginning of rising energy prices to the nation; 1986, the year in which energy prices began a ten-year decline in real terms; 1990, the year generally used as a reference for carbon emissions; 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 \$100 billion per year on R&D, dwarfing the government expenditure on all non-defense technology R&D. Of this 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.

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).

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 2.3 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%).

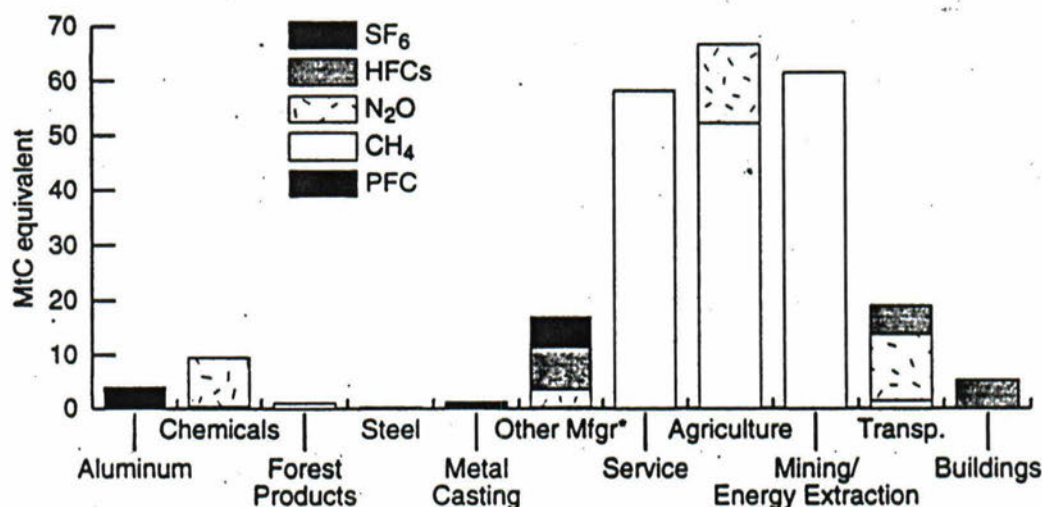
Table 2.4 Carbon Emissions from Fossil Energy Consumption: 1973 to 1997

	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-CO₂ 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 hexafluoride (SF₆). 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-CO₂ greenhouse gas contribution is from methane (CH₄), which is responsible for 177.5 MtC equivalent and has a GWP of 21. Next is nitrous oxide (N₂O), 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. SF₆ 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-CO₂ Greenhouse Gas Emissions by End-Use Sector and Industry



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).

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 (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-E 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, 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 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 public health benefits that have resulted from advances in energy-efficient and renewable energy technologies, and Romm (1994) describes productivity gains that have accompanied investments in industrial efficiency improvements.

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”, paper to be presented at the Thirty-Second Annual Intersociety Energy Conversion Engineering Congress, Honolulu, HI, July 27-August 1.

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

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

where: E_t is value in 1996\$ of energy saved in year t
 P_t is annualized cost premium (1996\$) of the better product

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