Scenarios *of* U.S. Carbon Reductions

Potential Impacts of Energy Technologies by 2010 and Beyond

Prepared by the

Interlaboratory Working Group on Energy-Efficient and Low-Carbon Technologies

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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 programs and policies to expand adoption of energy-efficiency and low-carbon technologies, an increase in the relative price of carbon-based fuels by $25 or $50/tonne (e.g., as a result of a cap on domestic carbon emissions and a market for carbon "permits"), and an aggressive program of targeted research and development. Current projections suggest that a carbon emissions reduction of 390 million metric tons per year (MtC/year) is required to stabilize U.S. emissions in 2010 at 1990 levels.

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

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

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

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

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

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

AUTHORSHIP

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

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

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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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Staff at Lawrence Berkeley National Laboratory (LBNL) and Oak Ridge National Laboratory (ORNL) put enormous efforts into producing this report, especially as contributions came from many different places. We gratefully acknowledge Barbara Maximovich, Leslie Shown, Sam Webster, and Nathan Martin (LBNL) and Tonia Edwards and Kathi Vaughan (ORNL) for word processing (BM and TE), copy editing (LS and NM), and cleanup of figures (KV and SW).

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).

This report benefited from the contributions and assistance of numerous experts on energy efficiency and electricity production. The authors would like to acknowledge contributors by chapter:

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

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

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

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

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

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ACRONYMS AND ABBREVIATIONS

AEO97	Annual Energy Outlook 1997
AFV	alternative fuel vehicles
Btu	British thermal units
CAAA	Clean Air Act Amendments (1990)
CAFE	Corporate Average Fuel Economy
CCAP	Climate Change Action Plan (1993)
CCE	cost of conserved energy
CD-50	clean diesel, 50% efficiency
CFCs	chlorofluorocarbons
C	carbon
CO	carbon monoxide
CO_2	carbon dioxide
DOE	U.S. Department of Energy
DSM	demand-side management
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
EPACT	Energy Policy Act
GDP	gross domestic product
GHG	greenhouse gas
GW	gigawatt (10^9 watt)
GWh	gigawatt-hour (10^9 watt-hours)
HE/LC	high-efficiency/low-carbon case
IGCC	integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
IPP	independent power producer
IRR	internal rate of return
kW	kilowatt (10^3 watt)
kWh	kilowatt-hour (10^3 watt-hours)
lb	pound
LIEF	Long-Term Industrial Energy Forecasting Model
MPG	miles per gallon
MtC	million metric tons of carbon
MW	megawatt (10^6 watt)
MWh	megawatt-hours (10^6 watt-hours)
NGCC	natural gas combined cycle
NEMS	National Energy Modeling System
NO_x	nitrogen oxides
NPV	net present value
O&M	operation and maintenance
quad	quadrillion (10^{15}) Btu
R&D	research and development
RD&D	research, development and demonstration
ROI	return on investment
SO_2	sulfur dioxide
T&D	transmission and distribution
tcf	trillion cubic feet
ton	short ton (2000 pounds)
tonne	metric ton (1000 kilograms)
VMT	vehicle miles traveled
VOC	volatile organic compounds

Chapter 1

ANALYSIS RESULTS

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

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

1.1 OBJECTIVES OF THE REPORT

The purposes of this study are threefold:

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

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

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

1.2 METHODOLOGY

To achieve these objectives, we started with the *Annual Energy Outlook 1997* (AEO97) reference case forecasts for the year 2010 (Energy Information Administration, 1996). After thoroughly reviewing these forecasts on a sector-by-sector basis, and working with EIA staff, we chose to accept the EIA "business-as-usual" (BAU) scenario as is for buildings and industry. We modified some of the assumptions and data to produce a new BAU case – not greatly different from the EIA case – for the transportation and the electric utility sectors.[2]

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

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

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

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

1.3 BACKGROUND

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

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

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

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

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

1.4 RESULTS

1.4.1 Prospects for Improved Efficiencies by the Year 2010

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

Table 1.1 Primary Energy Use in Quads: 1990-2010

	1990	1997	2010 Business-as-Usual Case	2010 Efficiency Case	2010 High-Efficiency/ Low-Carbon Case ($50/tonne C)
Buildings	29.4	33.7	36.0	34.1	32.0
Industry[a]	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.
[a] Excludes renewable energy; see Table 4.1 for more detail.

The major observations are as follows:

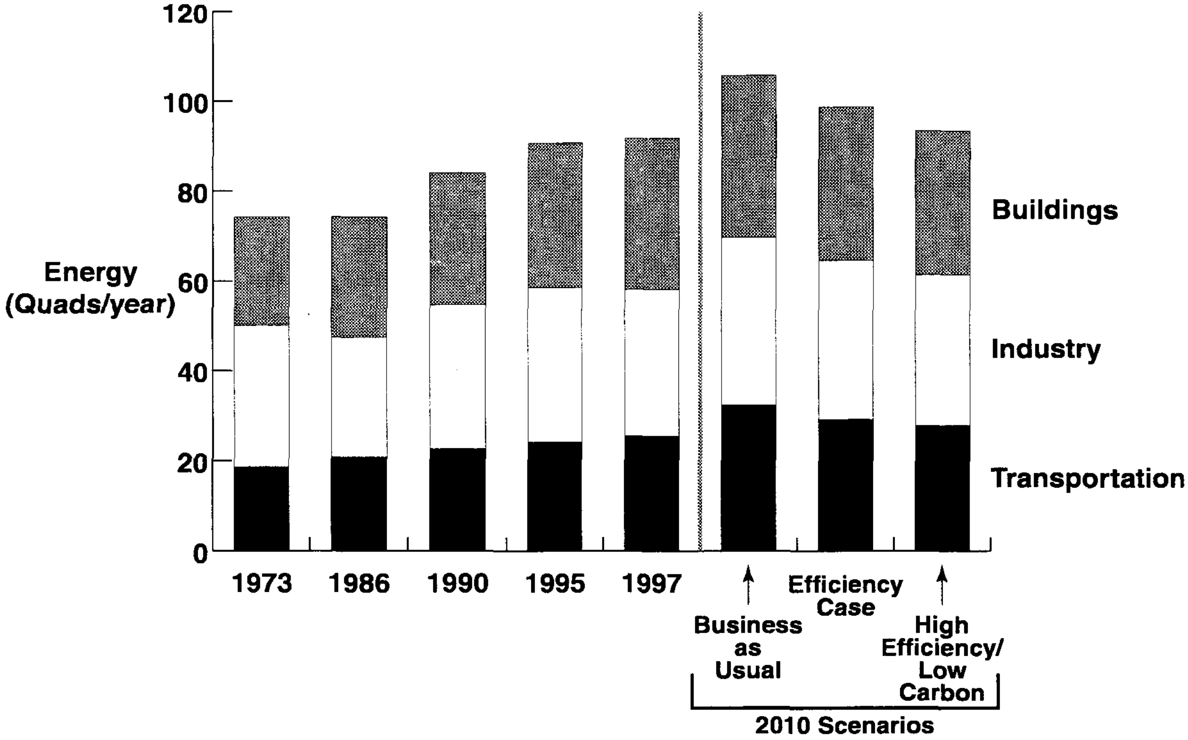
- In the business-as-usual case, energy use increases by 22 quads (26%) between 1990 and 2010; 8 quads of this increase have occurred during the first seven years of this 20-year period. The fastest growing sector during these initial seven years has been buildings (4.3 quads) followed by transportation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

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

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

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

Figure 1.1 Primary Energy Use in Quads: 1990-2010



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

Table 1.2 Carbon Emissions (MtC): 1990-2010

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

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

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

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

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

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

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

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

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

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

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

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

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

Figure 1.2 Reductions in Carbon Emissions from Each Scenario

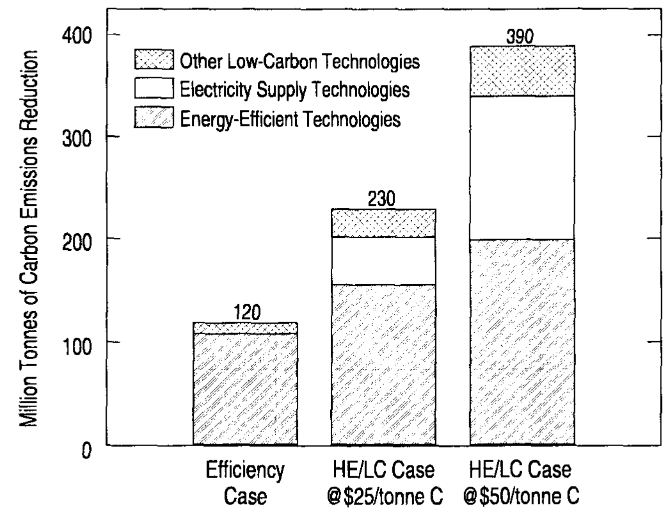


Figure 1.3 Reductions in Carbon Emissions from Each Type of Technology

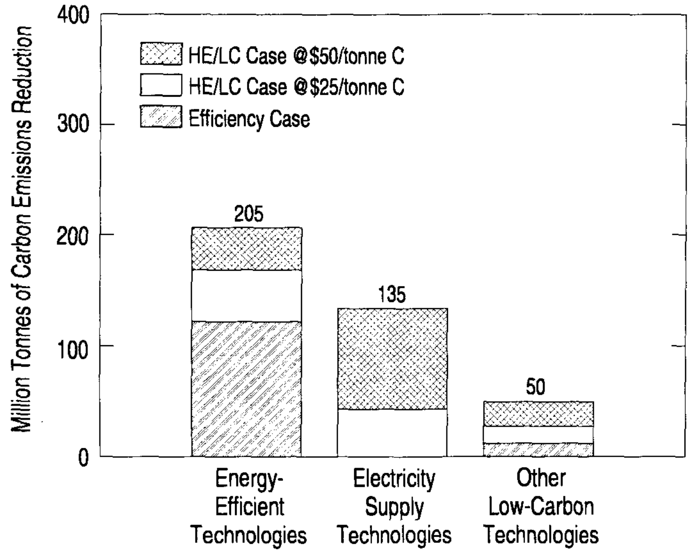


Table 1.3 provides a comparison of the growth rate in energy and in carbon emissions for the four cases, from 1997 to 2010. For the BAU and efficiency cases, the growth in carbon emissions is slightly more rapid than the increase in energy demand. For the HE/LC case with a $50/tonne carbon charge, carbon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

It is useful to compare the scenarios in this study to those of other studies. The 1991 report by the Office of Technology Assessment (OTA) titled *Changing by Degrees* (U.S. Congress, 1991) analyzed the potential for energy efficiency to reduce carbon emissions by the year 2015, starting with the base year of 1987. Its "moderate" scenario results in a 15% rise in carbon emissions, from 1300 MtC/year of carbon in 1987 to 1500 MtC/year of carbon in 2015 (compared to a BAU forecast of 1900 MtC/year). Its "tough" scenario results in a 20% to 35% emissions reduction relative to 1987 levels, or emissions levels of 850 to 1000 MtC/year of carbon in 2015. Our efficiency and HE/LC cases ranging from 1.3 to 1.6 billion tonnes of carbon emissions in 2010 are comparable to OTA's "moderate" case and show considerably higher emissions than OTA's "tough" case.

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

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

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

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

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

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

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

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

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

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

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

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

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

In the next quarter century, improved energy-efficiency technologies will result from a combination of incremental advances and fundamental breakthroughs. Incremental improvements in all sectors can be achieved by the greater reliance on more precise and reliable sensors and controls or on lower-cost sensors and controls, often integrated into industrial processes, transportation systems, and buildings. Advanced manufacturing technologies, including rapid prototyping and ultraprecision fabrication, also offer broad opportunities for continuous incremental improvements in energy efficiency and renewable energy. Breakthroughs in bioprocessing, separations, superconductivity, catalysts, and materials can have wide-ranging impacts on energy efficiency and carbon emissions by the year 2020. Examples of specific technology opportunities are described in this report, by sector.

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

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

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

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

- Breakthroughs in manufacturing processes for composite materials,
- Large reduction in fuel cell costs and/or cost reductions and performance gains in batteries,
- 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 this report.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

The results of the economic analysis are presented in Table 1.5. Estimated direct costs are $25-$50 billion per year for the efficiency scenario and $50 to $90 billion per year for the high-efficiency/low-carbon scenario. Estimated energy savings per year in 2010 are $40 to $50 billion per year in the efficiency case and $70-$90 billion per year for the high-efficiency/low-carbon case. The costs, which are a small portion of annual gross private domestic investment of about $1.4 trillion in 2020, are likely to be more than balanced by savings in energy bills. Thus, net costs to the U.S. economy are estimated to be near or below zero in this time frame.

The range of estimates in Table 1.5 reflects our attempt to "bound" optimistic and pessimistic assessments. There are clearly other ways in which these bounds could be described, just as there are many scenarios that could have been analyzed. We reflect a lower or pessimistic bound in three ways. First, we assume the investments in energy efficiency yield only 80% of the estimated energy savings. Second, we value costs and benefits at discount rates noticeably higher than the likely cost of capital. Third, we increase the estimated cost of programs and policies to twice that of typical experience today. It is worth noting that if the implementation costs were taken to be much higher than we believe to be reasonable – 50% of investments costs for programs and 25% overall – this would add about $10 billion per year to the costs of the high-efficiency/low-carbon in the pessimistic case.

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

	Efficiency Case[a]			High-Efficiency/Low-Carbon Case[b]		
	Direct Costs[d] (billion 1995$)	Energy Savings[c] (billion 1995$)	Carbon[c] Savings MtC	Direct Costs (billion 1995$)	Energy Savings (billion 1995$)	Carbon Savings MtC
Energy Efficiency						
Buildings	7-14	14-17	20-25	14-26	26-33	49-62
Industry	3-5	6-7	22-27	8-13	12-15	74-93
Transportation	16-30	22-27	58-73	23-43	32-40	82-103
Power Plant Retirement & Redispatch	0	0	0	2	0	44-55
Electricity Repowering	0	0	0	2	0	32-40
Other Low-Carbon Technologies	0	0	0	2	0	33-41
Total	**25-50**	**40-50**	**100-125**	**50-90**	**70-90**	**310-390**

[a] Energy efficiency category includes ethanol in transportation.

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

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

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

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

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

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

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

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

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

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

1.6 REFERENCES

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ENDNOTES

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

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

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

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

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

Chapter 2
INTRODUCTION AND BACKGROUND

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

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

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

2.1 OBJECTIVES OF THE STUDY

The purposes of this study are threefold:

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

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

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

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

2.2 METHODOLOGY

2.2.1 Overview

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

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

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

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

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

2.2.2 Time Frame

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

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

2.2.3 End-Use Efficiency Scenarios

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

2.2.4 Methodological Differences Across Sectors

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

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

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

Table 2.1 Conceptual and Operational Definitions of Scenarios for 2010

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

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

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

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

2.2.5 What the Study Does Not Do

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

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

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

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

2.3 OVERVIEW OF THE REPORT

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

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

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

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

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

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

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

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

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

2.4 HISTORICAL ENERGY TRENDS

2.4.1 National Trends

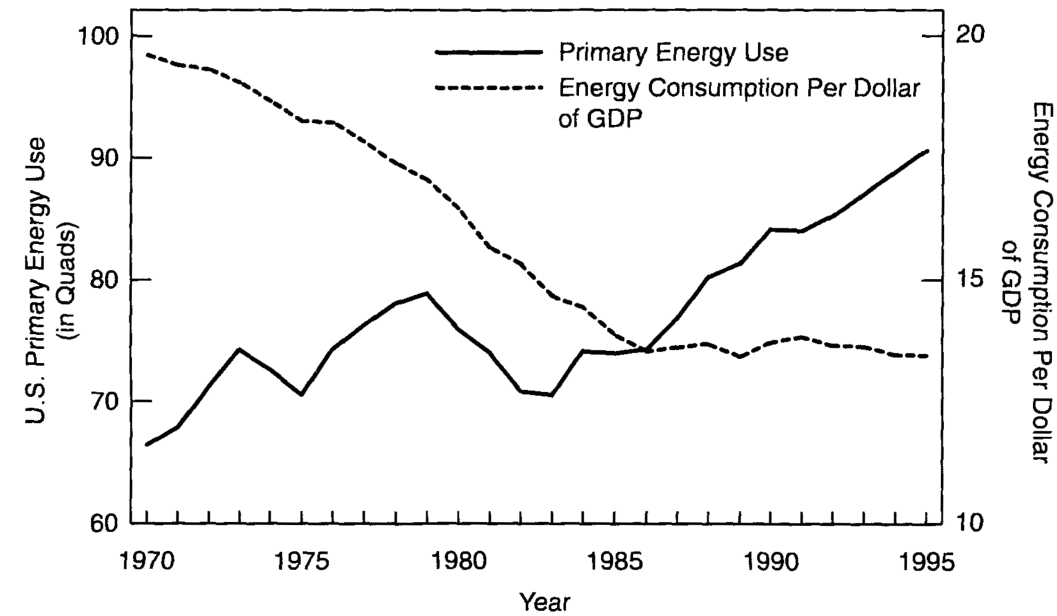
In studying historical trends in energy use and carbon emissions, we have chosen to highlight the years 1973, the beginning of rising energy prices to the nation; 1986, the year in which energy prices began a ten-year decline in real terms; 1990, the year generally used as a reference for carbon emissions;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

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

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

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

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



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

2.4.2 Sectoral Trends

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

The principal causes of energy inefficiencies in manufacturing and transportation are not the same as the causes of inefficiencies in homes and office buildings, although there are some similarities (Hirst and Brown, 1990). For example, in the manufacturing sector, energy-efficiency investments are hindered by a preference for investments that increase output compared with investments that reduce operating costs. The cost and relative difficulty of obtaining reliable information often prevents energy-efficient features of buildings from being capitalized into real estate prices. This is partly due to the lack of widely accepted building energy rating systems. These same information gaps do not characterize the transportation sector, which has a well understood labeling system for vehicles, in the form of miles per gallon. Misplaced incentives inhibit energy-efficient investments in each of the sectors. Consumers often must use the energy technologies selected by others. Specialists write product specifications for military purchases that limit access to alternatives. Fleet managers select the vehicles to be used by others. And architects, engineers, and builders have great control over the energy integrity of buildings, even though they do not pay the energy bills. The involvement of intermediaries in the purchase of energy technologies limits the ultimate consumer's role in decision making and leads to an emphasis on first cost rather than life-cycle cost (DOE, 1996b).

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

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

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

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

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

Table 2.2 Primary Energy Use in Quads: 1973-1997

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

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

Table 2.3 Historical Energy Growth Rates: 1973-1997

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

AAGR = Average Annual Growth Rate

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

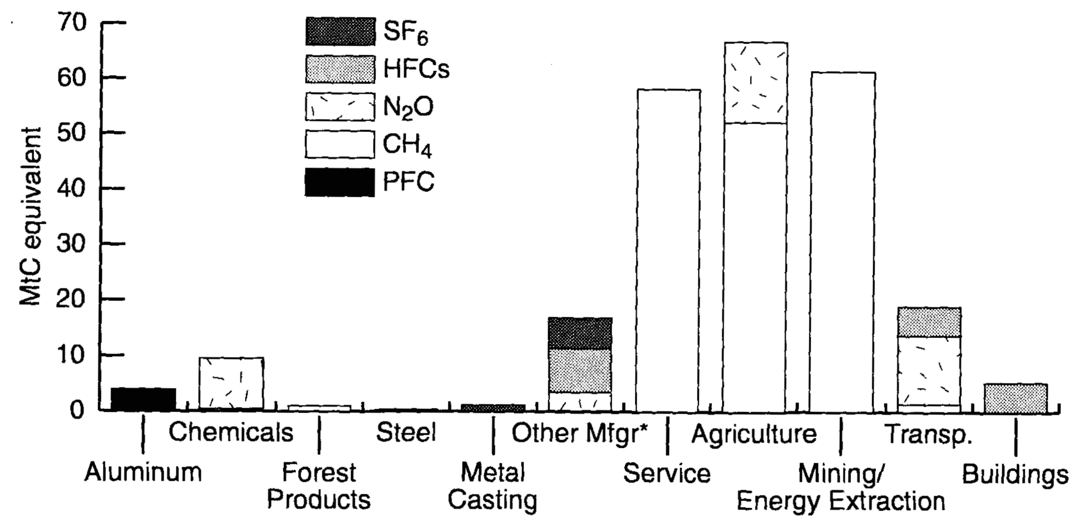
Table 2.4 Carbon Emissions from Fossil Energy Consumption: 1973 to 1997

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

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

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

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



* Mainly semiconductors

Source: EIA (1996b)

2.5 THE GOVERNMENT'S ROLE IN ENERGY R&D

2.5.1 Rationale for Government Support

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

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

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

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

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

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

2.5.2 Past R&D Successes

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

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

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

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

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

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

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

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

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ENDNOTES

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

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

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

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

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

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

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

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

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

Chapter 3
THE BUILDINGS SECTOR

3.1 INTRODUCTION

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

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

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

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

3.2 PROVEN AND NEAR-TERM TECHNOLOGIES

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

3.2.1 Generic Assumptions

Our approach is based on a stock accounting framework of building and equipment types. For all scenarios, base case growth in households and commercial floorspace tracks historical trends. This results in a net total 2010 stock that is greater than 1997 levels by 15% and 12% in residential and commercial buildings, respectively, taking account of new building construction and retirement of existing stock. Retrofit or replacement of existing "shells" (walls, roofs, windows, doors) and equipment is a function of their average lifetimes. We assume that, on average, residential and commercial building shells last 100 and 50 years, respectively, and thus only a small portion of buildings are replaced during the study period with a much larger fraction undergoing some shell retrofit. In contrast, average equipment lifetimes range from one year (for lights) to 20 years (for furnaces). All equipment with lifetimes significantly less than the forecast period (13 years), such as residential lighting, will be replaced but only a portion of the equipment with lifetimes comparable to or longer than the forecast period will be replaced. The combination of shell and equipment turnovers results in four categories of buildings in our model: (1) old buildings with old equipment; (2) old buildings with new equipment; (3) retrofit building shells with new equipment; and (4) new buildings with new equipment.

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

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

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

3.2.2 Scenario Definitions

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

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

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

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

3.3 SCENARIOS FOR THE YEAR 2010

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

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

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

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

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

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

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

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

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

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

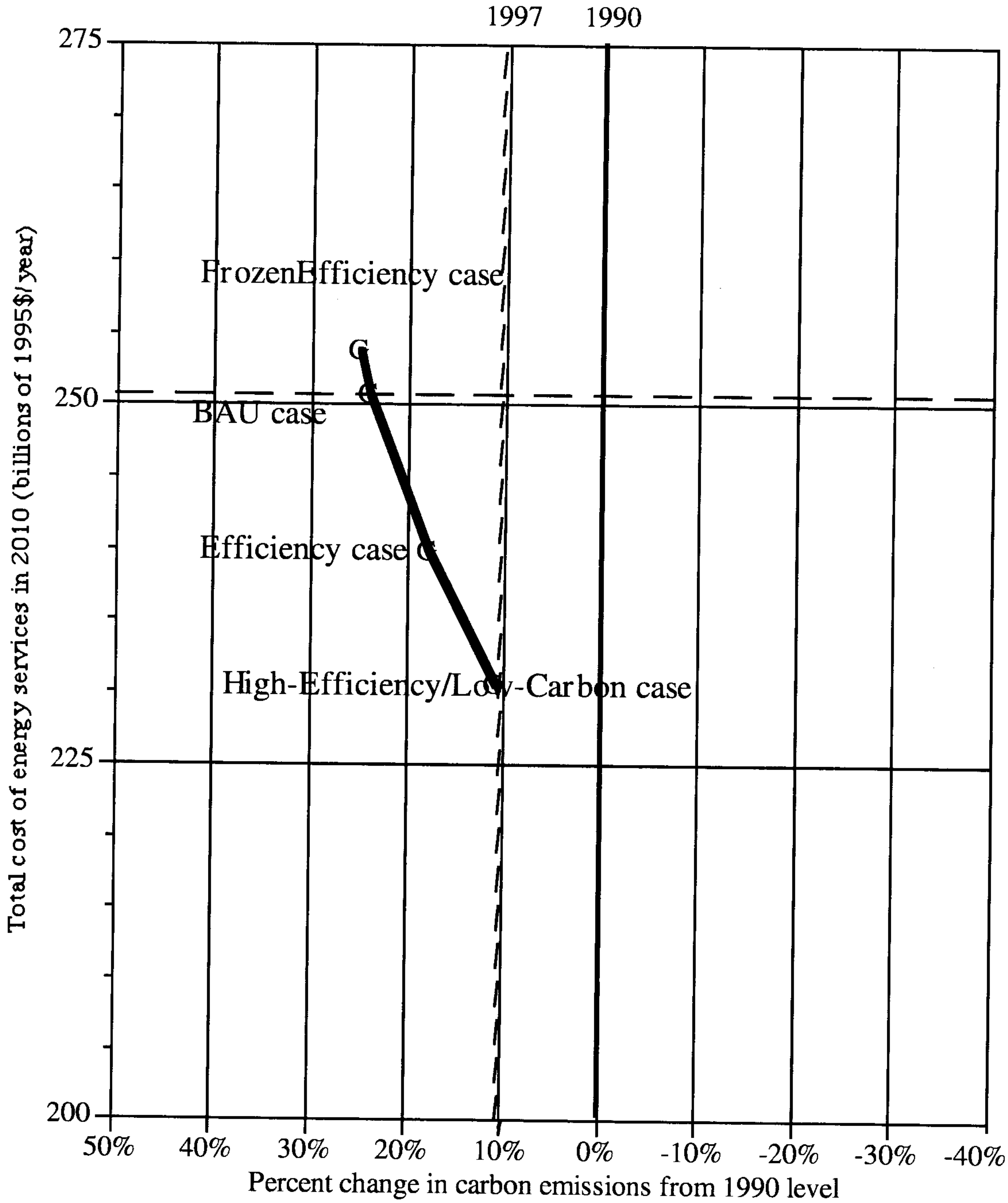
Note: Table does not include effects of building-sector fuel cells. Numbers may not add to the totals due to rounding.

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

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

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

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



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

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

Notes: A portion of the reduction in carbon emissions associated with the high-efficiency/low-carbon case is due to changes in the electricity generation mix prompted by the charge of $50/tonne of carbon. Total cost of energy services includes costs of purchasing fuel and electricity as well as the annualized incremental cost of efficiency improvements relative to the business-as-usual case. Figure does not include effects of building-sector fuel cells.

3.3.1 Business-as-Usual Scenario

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

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

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

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

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

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

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

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

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

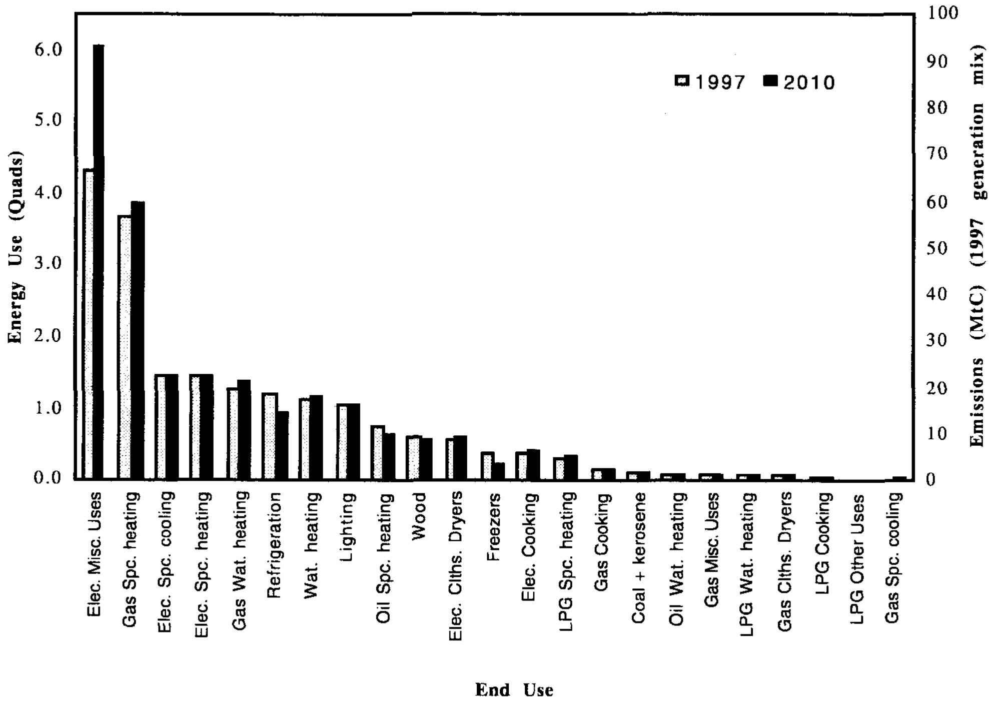
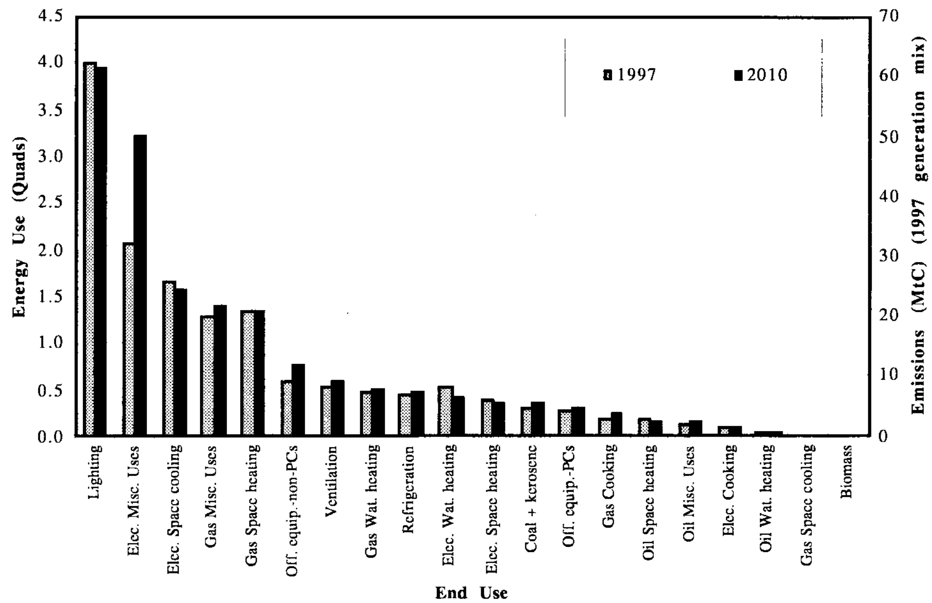


Figure 3.3 Commercial Sector Primary Energy Use and Carbon Emissions in 1997 and 2010 by End-Use for the Business-As-Usual Scenario



3.3.2 Maximum Cost-Effective Energy-Efficiency Potential

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

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

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

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

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

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

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

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

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

Figure 3.4 End-Use Electricity Savings, 2010

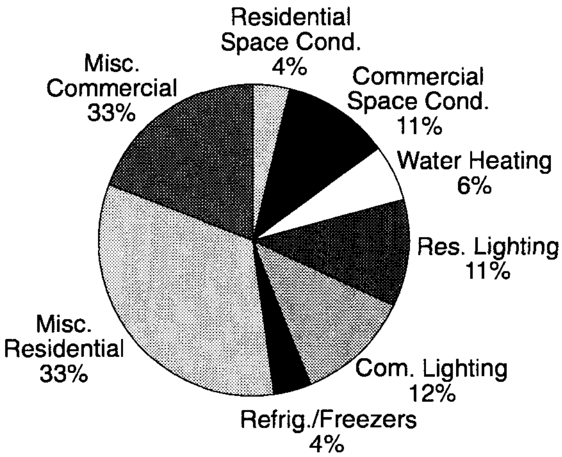
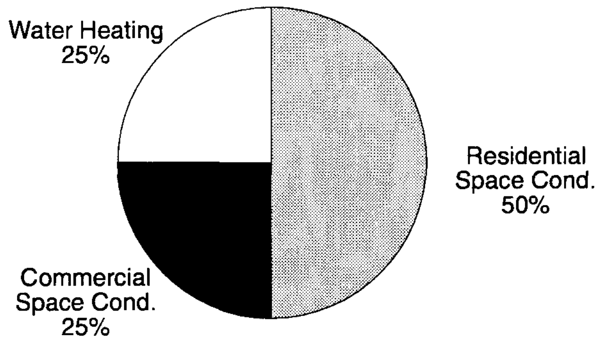


Figure 3.5 End-Use Natural Gas Savings, 2010



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

3.3.3 Efficiency Scenario Results

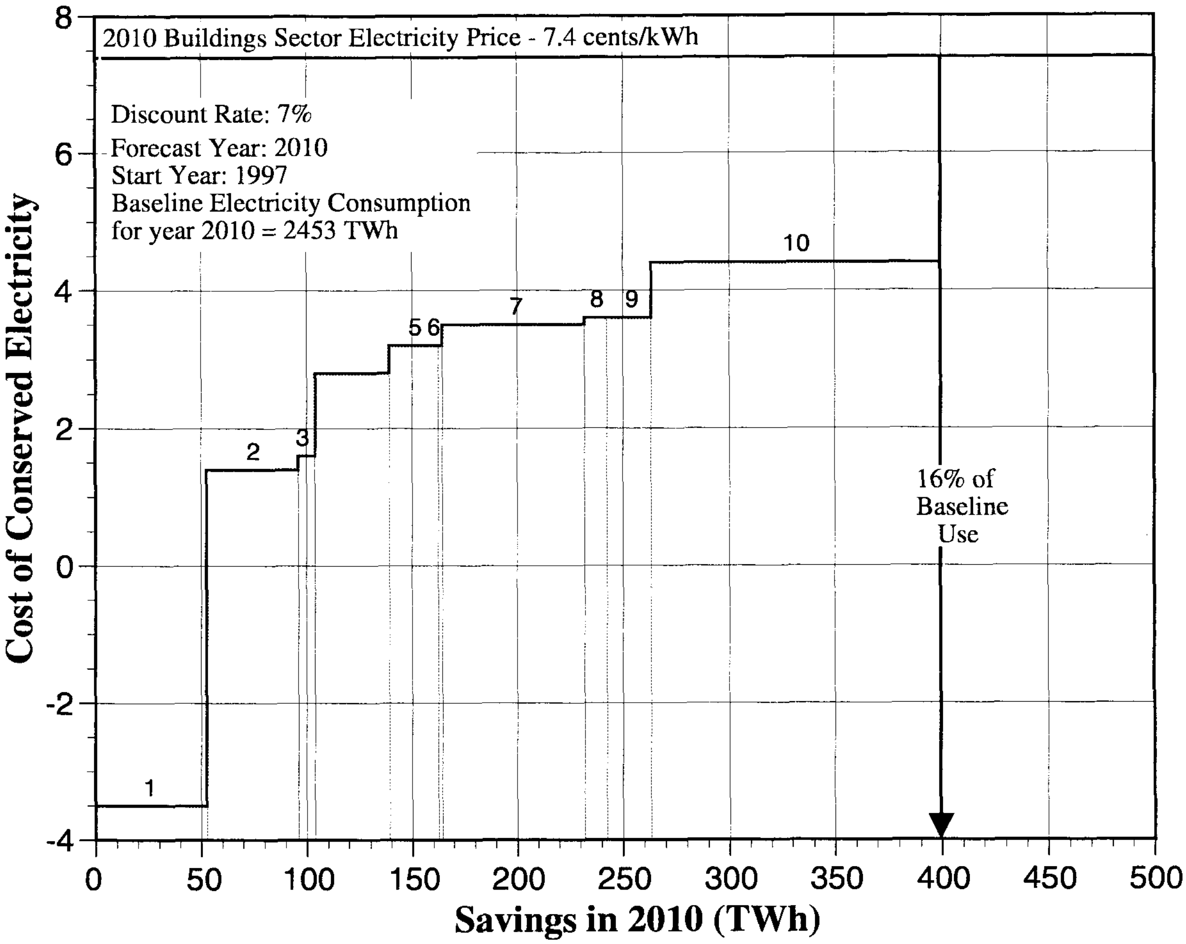
The efficiency scenario assumes that 35% of the maximum cost-effective efficiency savings are achieved by 2010. This assumption is based on expected savings resulting from a moderately vigorous effort to reduce energy use and carbon emissions using a combination of policy mechanisms that may include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

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

3.3.4 High-Efficiency/Low-Carbon Scenario Results

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

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



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

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

Improving Efficiency and Saving Capital

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

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

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

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

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

3.4 POTENTIAL FOR ADVANCED TECHNOLOGIES IN 2020[6]

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

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

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

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

3.4.1 New Technologies and Practices

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

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

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

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

3.4.1.1 Advanced Construction Methods and Materials

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

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

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

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

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

3.4.1.2 Environmental Integration and Adaptive Envelopes

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

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

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

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

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

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

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

Mitigating Urban Heat Islands With Cool Roofs And Trees

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

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

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

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

3.4.1.3 Multi-Functional Equipment and Integrated System Design

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

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

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

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

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

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

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

3.4.1.4 Advanced Lighting Systems

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

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

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

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

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

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

Lighting controls have only recently advanced beyond simple on-off, multi-level, or time clock controls to occupancy-based controls and photosensor controls that respond to daylight and lumen maintenance. By 2020, new generations of smart control systems will respond automatically to changing task and environmental needs. Voice-activated controls and flexible linkages (wired and wireless) between light sources and tasks will provide new flexibility in both office and retail environments. Controls linked to dimmable lighting systems and to building energy management control systems (EMCS) will provide an equivalent spinning reserve load that can be used by owners when negotiating utility contracts with electricity suppliers in the deregulated environment of 2020.

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

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

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

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

3.4.1.5 Controls, Communications, and Measurement

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

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

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

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

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

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

3.4.1.6 Self-Powered Buildings

The move toward a competitive marketplace for energy services such as gas and electricity will be essentially complete by 2010. By 2020, that market will have matured to accommodate complex buy-sell utility service arrangements monitored and administered by automated systems. This, combined with the advent of power production and improved energy storage technologies, will give building owners new levels of flexibility in meeting their energy requirements, as well as the possibility of revenue streams from the sale of energy or ancillary services. Buildings will cease to be simply consumers of electric utility services but may supply all or a portion of their own energy requirements or, if the economics are right, sell to others. Removal of utility and environmental regulatory barriers would also accelerate the adoption of combined heat and power systems.

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

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

Potential Additional Savings From Advanced Fuel Cell Technologies

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

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

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

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

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

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

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

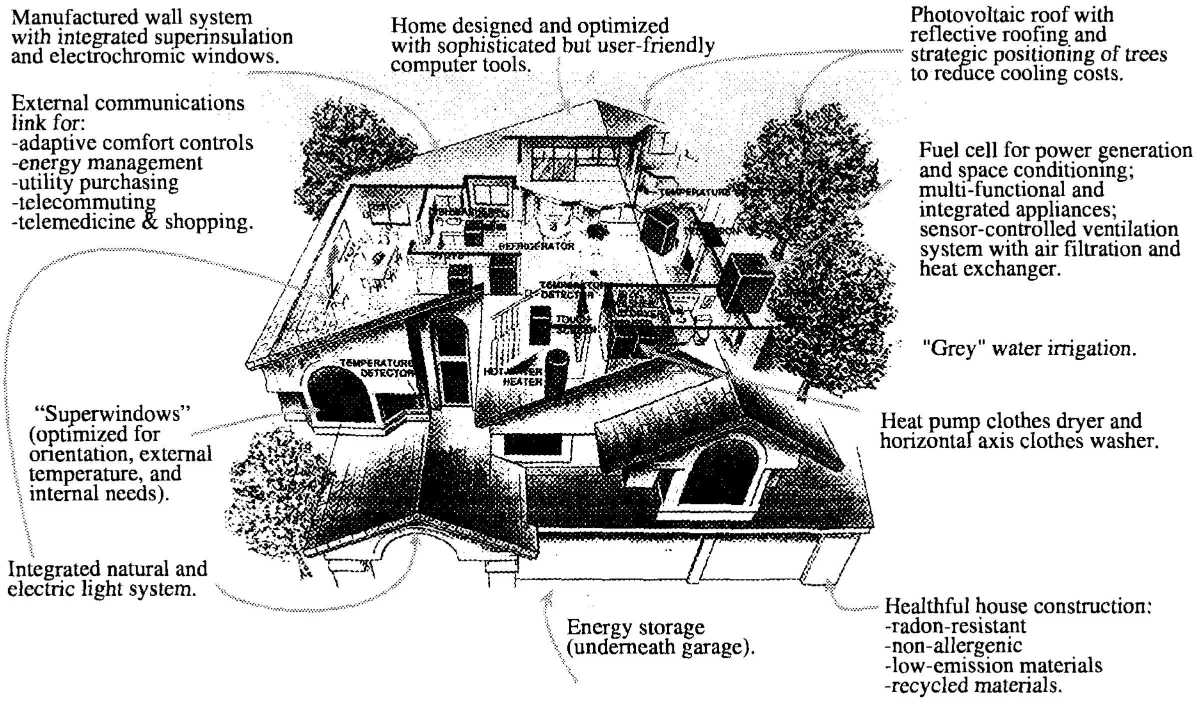
3.4.2 Best Practice Buildings in the Year 2020

3.4.2.1 "Best Practice" Housing in 2020

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

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

Figure 3.7 "Best Practice" Home of the Year 2020



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

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

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

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

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

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

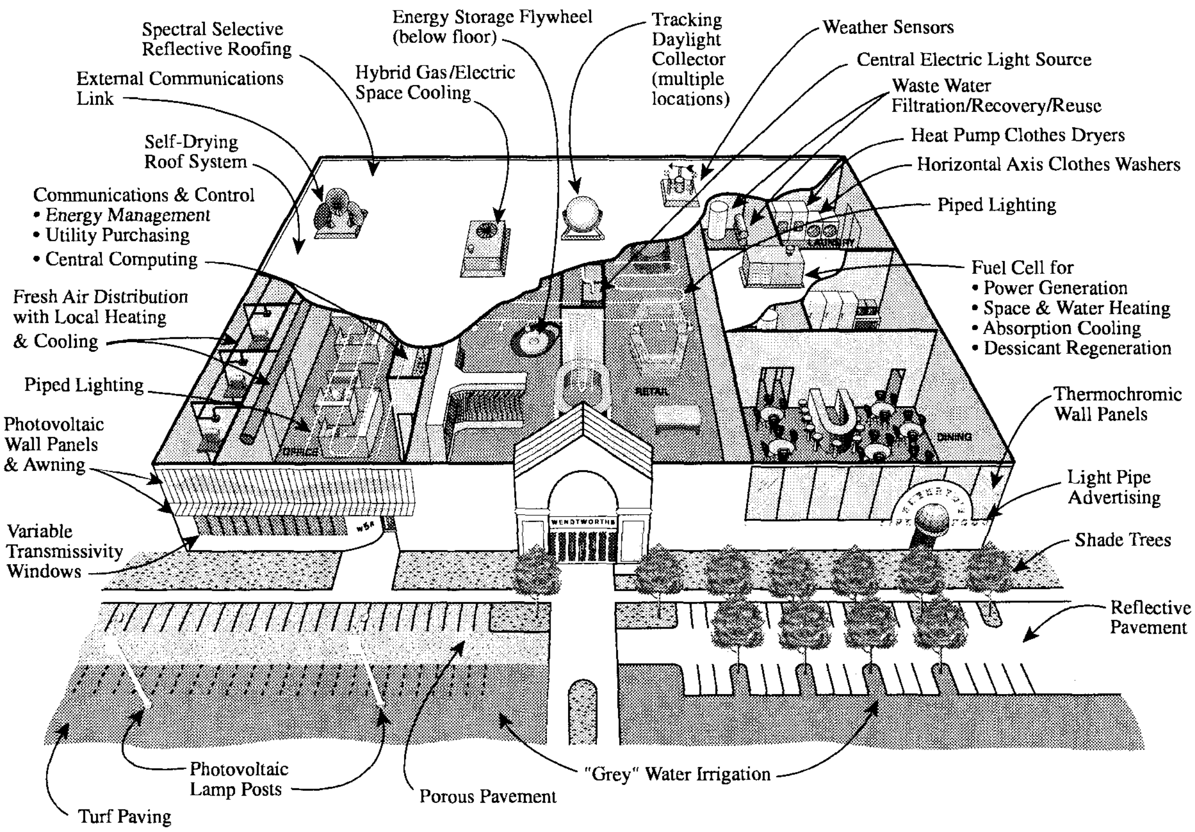
Home computers and sophisticated communication systems will begin to permit the use of the home as the location of office, secondary school, routine medical treatment, and selected shopping activities. This will begin to change the "mix" of building types as well as the need to commute to these activities.

3.4.2.2 "Best Practice" Commercial Buildings in 2020

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

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

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



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

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

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

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

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

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

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

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

3.5 IMPROVEMENTS TO THIS ANALYSIS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.6 SUMMARY AND CONCLUSIONS

Our analysis leads to the following key results for 2010:

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

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

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

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

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

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

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

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

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

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

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

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

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

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ENDNOTES

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

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

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

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

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

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

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

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

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

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

Chapter 4

THE INDUSTRIAL SECTOR

4.1 INTRODUCTION

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

4.1.1 Approach

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

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

4.1.1.1 Scenario Analysis

For the scenario portion of the analysis, the ideal analytical tool would be an industrial model that is publicly-available, complete and up-to-date, and has a stock-adjustment mechanism as well as detailed, technology-specific conservation supply curves for all important industrial processes that are affected by energy prices, capital recovery rates, and other economic parameters. We would also like to be able to relate the modeling results to those reported in the US. Department of Energy's *Annual Energy Outlook 1997* (AEO97), which is prepared by the Energy Information Administration using the National Energy Modeling System (NEMS) (EIA 1997b).

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

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

4.1.1.2 Technology Examples

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

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

Energy-Intensive Industries

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

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

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

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

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

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

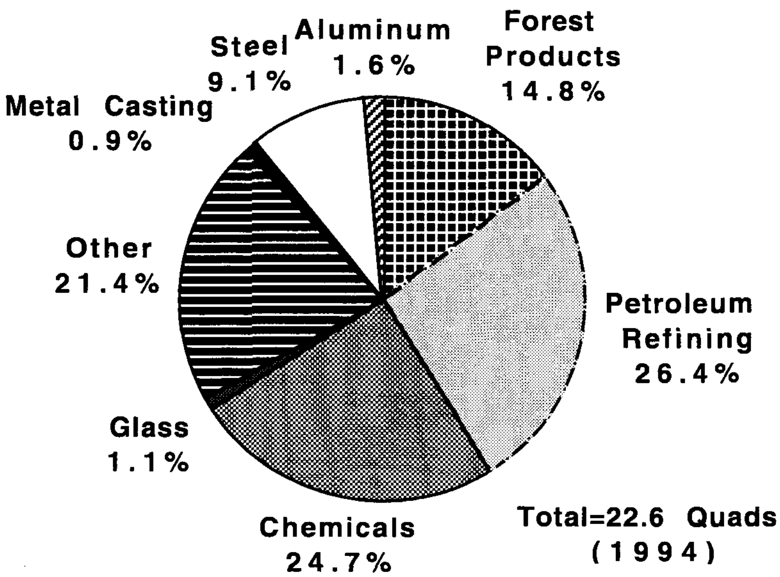
Stone, Clay and Glass Products. "Nonmetallic Mineral Products," under NAICS, includes cement, glass (a Vision Industry), bricks, lime, and other stone and ceramic products. Pyroprocessing, or the application of heat to assure a chemical reaction, is required in most of these subindustries, which is what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

4.1.1.3 A Continuing Stream of New Technologies

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

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

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



4.2 ENERGY EFFICIENCY EMISSIONS REDUCTIONS

The LIEF model contains conservation supply curves for various industries that correlate energy conservation investment as a function of energy prices. These curves have been calibrated to historical industry data using an implicit Capital Recovery Factor (CRF) of 33%. CRFs and associated discount rates at this level or higher – representing a requirement that these investments pay back the capital outlay within a few years – have been found to characterize much of the decision-making in industry on investments in energy-efficiency technologies and on similar investments. At the same time, firms have another class of investment decisions – termed "strategic" investments – that are characterized by a lower CRF or discount rate (i.e., the initial investments are allowed to pay back over a longer period) (see Ross 1990). One way, then, to simulate an increased investment in energy-efficient technology is to postulate a policy or set of policies that would lead industry to apply something like this more "strategic" discount rate to energy-efficiency investments. This effect could be induced via policies that served to decrease the first cost of such investments or that resulted in increased annual cost savings.

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

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

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

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

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

Policies that might reduce these effects are:

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

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

4.2.1 Business-as-Usual Case

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

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

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

4.2.2 Efficiency and High-Efficiency/Low-Carbon Cases

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

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

Table 4.1 summarizes the results in the energy consumption levels forecast by the AEO97. The overall change in energy use between 1997 and 2010 is shown for the BAU case in the first two columns for fossil fuels and electricity use (including system conversion losses). Renewables, feedstocks and non-energy uses of petroleum (e.g. asphalt, waxes, lubricants, etc.) are also shown, but are unaffected by the LIEF analysis. The next two columns show the effects of the efficiency case and the HE/LC case, as forecast by LIEF, on the AEO97 BAU case. Figure 4.2 shows that the HE/LC case approaches zero growth with energy use increasing by only 1.4 quads (4%) between 1997 and 2010, in spite of an output increase of 30% over the period.

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

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

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

* Expanded renewable use is considered in Section 4.3.

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

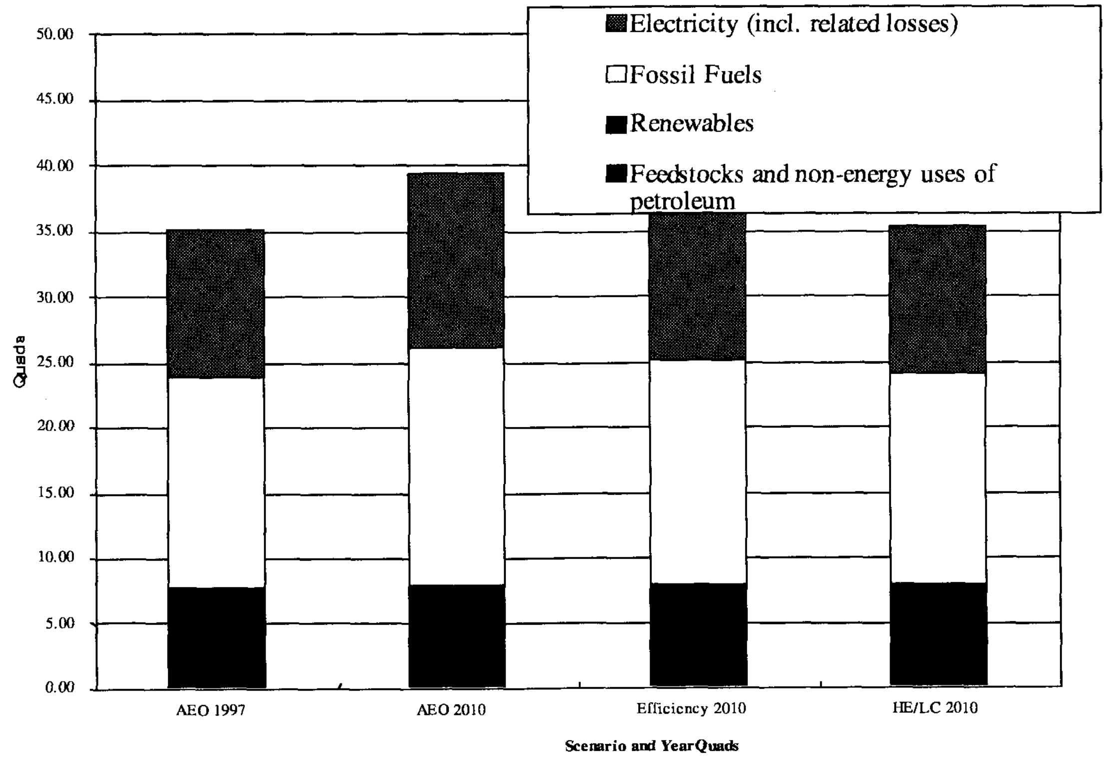


Table 4.2 shows the results of these analyses for ten major economic sectors of U.S. industry.[1] The results in Table 4.2 are expressed in terms of an additional annual percentage reduction in sectoral energy intensity compared with the BAU case. The efficiency case reduces total energy intensity growth by an additional 0.5% per year. The HE/LC case reduces the growth in energy intensity by over 1% per year, relative to the BAU case, and reduces the growth in electricity use by more than 1% annually (1.3%).

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

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

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

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

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

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

The second is that the growth in output for light industry is much higher than for heavy industry. Output grows more than 80% by the year 2010 for light industry, but only 30% for heavy industry. As a result, in the BAU case, electricity demand nearly doubles for light industry and fossil fuel use grows more than 60%. Fossil fuel demand for heavy industry only increased by 12% in the BAU case, while electricity demand increases by 48%.

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

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

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

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

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

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

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

Table 4.4 Change in Industrial Energy Use by Fuel Type

	AEO		Efficiency	HE/LC
	1997	2010	2010	2010
Natural gas (billion cu ft)	9,914	11,103	10,303	9,564
Coal and coke (1000 short tons)	104,716	113,741	10,551	97,976
Liquid fuels - incl. LPG (1000 bbl)	695,160	697,300	647,090	600,648
Petrochemical feed stocks & other petroleum (1000 bbl)	925,536	1,180,979	1,180,979	1,180,979

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

Table 4.5 Carbon Emissions Estimates (MtC per year)

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

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

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

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

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

	Efficiency			HE/LC		
	Electric	Fuels	Total	Electric	Fuels	Total
Heavy Manufacturing	2.1	7.1	9.2	5.9	14.8	20.6
Pulp & Paper	0.3	1.1	1.5	1.0	2.3	3.3
Bulk Chemicals	0.7	1.5	2.2	1.9	3.2	5.1
Petroleum	0.3	2.5	2.7	0.6	5.2	5.8
Glass	0.1	0.2	0.2	0.2	0.3	0.5
Cement	0.0	0.2	0.3	0.1	0.5	0.6
Iron & Steel	0.4	1.2	1.6	1.1	2.3	3.4
Aluminum	0.1	0.0	0.2	0.4	0.0	0.4
Other	0.2	0.4	0.6	0.6	0.9	1.5
Light Manufacturing	6.3	5.2	11.5	17.8	9.7	27.4
Non-Manufacturing*	1.3	5.7	7.0	3.4	10.4	13.8
Total	9.6	18.1	27.7	27.0	34.9	61.9

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

4.2.3 Comparison with the NEMS model

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

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

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

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

4.2.4 The Historical Context of Energy Efficiency in Industry

Over time, both the "what" and the "how" of industry output changes. Buggies and whips have disappeared, but automobile production has taken their place. And while the Model T was mass-produced, today's methods of production are only vaguely reminiscent of Henry Ford's assembly line. Energy use in manufacturing and other industry sectors has changed due to both product and process transformation. Energy use changes occur because of energy-efficiency improvements over time as well as changes in the mix of industries. Rough approximation of the importance of these two factors indicates that efficiency accounts for about two-thirds of the change, while the shift in the mix of industries accounts for about one-third. Put into historical perspective, forecasts of energy use and energy intensity changes used for this analysis are modest changes and, we believe, more than just possibilities. With appropriate and effective policy measures to accelerate the adoption of technologies that are currently, or will soon be, available, the efficiency gains and energy and carbon savings projected could easily be achieved.

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

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

4.2.5 The Costs of Achieving the Efficiency and HE/LC Cases

The LIEF model conservation supply curves can be used to compute the investment implied by the forecast energy reductions. These estimates, shown in Table 4.8, are the additional investment required to achieve the energy savings presented above. Due to the long-lived nature of industrial capital goods, this cumulative investment in more efficient and productive industrial plant and equipment continues to generate energy and costs savings, relative to the base case, after the 2010 time horizon.

LIEF projects that this level of investment is profitable with the BAU forecast energy prices and a CRF of 15%. The energy savings provides about a seven-year payback on the initial investment. The magnitude of the up-front costs, which are paid back only over time, may be an issue in designing policies to spur this enhanced technology penetration.

To put this level of investment in energy efficiency into context, we compare it to total investment in manufacturing. If the cumulative investment in energy efficiency is spread out evenly over the 13-year time period, the HE/LC case would require a $3.6 billion increase in annual investment in efficiency technology. In 1992, total investment in manufacturing (not including agriculture, construction, and mining) was $110.1 billion (1995$). Thus, the incremental annual investment needed to achieve the HE/LC case represents a 3.3% increase over the level of manufacturing investment for 1992.

Table 4.8 Cumulative Incremental Investment (1998-2010) for Energy Efficiency Implied by the LIEF Model to Achieve the Forecast Energy Reductions (billions of 1995$)

	Efficiency Case	HE/LC Case
Fossil Fuels	7.4	15.2
Electricity	15.8	32.0
Total	23.2	47.2

Historical behavior with respect to energy efficiency investments has been characterized by implicit marginal discount rates equivalent to 33% capital recovery. The efficiency case is based on the notion that the marginal return on energy efficiency will be closer (or equal) to a *strategic* discount rate, represented here as a 15% CRF. For example, this translates to a marginal real return of 12.5% per year on a 15-year investment, which we will use for illustrative purposes. It is from this perspective that the efficiency case reflects 'cost-effective' investments. The 'last' investment will produce cost savings that will provide a return of 12.5%; other investments will generate higher returns. On average, the return will be higher than the marginal, or 'last', energy-efficiency project.

Table 4.9 shows the private investment cost of an investment in efficiency in a *single year* , compared to the value of the energy savings that would continue to accrue thereafter. The first line in the table is the incremental investment in the last year of our forecast, 2010. The second and third lines are the change in consumption and expenditure of energy for that year, which are negative since energy consumption is reduced. One can see that investments generate annual savings of about a third of the initial outlay. This is an average return that is quite a bit higher than the assumed marginal return of 12.5%. Recall that the marginal return is the 'last' cost-effective investment, which just pays for itself at the 12.5% rate.

Table 4.9 also shows the total energy savings and direct private costs of the scenario. These costs are generated using the cost of conserved energy (CCE) method detailed in Appendix A-1.3. For the efficiency scenario the energy savings exceed the direct private investment costs by $4 billion. The HE/LC scenario has energy savings in excess of direct investment costs of $7 billion.

Table 4.9 Net Costs of Private Investment for Energy Savings in the Efficiency and High-Efficiency/Low-Carbon Cases (millions of 1995$)

		Efficiency		HE/LC	
	Units	Fossil Fuels	Electric (End-use)	Fossil Fuels	Electric (End-use)
Investment in 2010	M$	$800	$1,700	$1,500	$3,200
Annual Energy Reduction	TBtu	94	47	178	82
Annual Reduction in Energy Costs	M$	$300	$600	$600	$1,100
Total Energy Redirection	TBtu	900	336	1800	685
Total Investment Cost	M$	$1,100	$1,800	$2,400	$4,100

Note: Costs are based on the annualized costs over the time period, not the cummulative investments.

We believe that most, if not all, of the difference between the observed behavioral CRF of 33% and the 15% CRF is due largely to factors that preclude firms from using these lower marginal rates for energy-efficiency investments, such as transaction costs, agency costs, the lack of information or the cost of acquiring it, perceived risk, etc. However, policies will be required to remove these factors and shift investment behavior to prioritize energy efficiency the same as other corporate investment. These policies will have a public cost.

The HE/LC case also focuses on 'cost-effective' investment under the same notion of these lowered, strategic, marginal rates of return. However, one important difference in the HE/LC scenario is that a higher adoption rate is assumed. While some additional penetration, relative to the BAU, may be accounted for by further transformation of the market of energy-efficient practices we feel that some accelerated retirement may also take place. When the economic losses of accelerated retirement are accounted for, this implies that, at the margin, all investments are not likely to be cost-effective at our assumed 15% CRF. Since we do not have a model to account for this potential early retirement and the economic losses, we must caveat our estimates of investment. The energy savings from the HE/LC scenario in Table 4.9 does not change, but the investment cost may be understated by the amount of loss due to any early retirement that may occur. Because the net benefit is still greater than the annualized investment we calculate, then unaccounted costs may be about twice our estimated energy-efficiency investment, with the HE/LC scenario remaining 'cost-effective' on average.

A carbon-based fuel price increase was considered and simulated using LIEF for a number of carbon shadow prices. Energy price increases alone do not have a very dramatic effect on energy use in the LIEF model. While they do have some affect on the options to reduce energy use, they have no endogenous affect on the rate of penetration of new technology in the model. For example, a $50 shadow price for carbon increases shifts the "ideal" energy-output ratio by only 8.5% for electricity and 5% for fossil fuel. The gap between the ideal and actual energy-output ratios is a measure of the conservation potential for the sector. Under the BAU case, this gap is 3.8% for electricity and 4% for fossil fuel. Under the EFF case, this gap is 27.6% for electricity and 15.3% for fossil fuels. Under the $50 shadow price case, the gap is 9.5% for electricity and 7% for fossil fuels. To achieve the same ideal energy-output ratio as the HE/LC case would require a shadow price of $250 for fossil fuels and $300 for electricity. Table 4.10 shows the carbon reduction and the percentage reduction in electricity and fossil fuels that result from simulation of different carbon shadow prices.

Table 4.10 Effect of Different Carbon Shadow Price Simulations on Electricity and Fossil Fuel Reductions

Shadow	Electricity		Fossil Fuels	
Price of Carbon	% of BAU	Carbon Saved	% of BAU	Carbon Saved
25	98.4	3	99.0	3
50	97.1	6	98.2	6
100	95.1	10	96.9	10
200	92.2	16	94.8	17
300	90.1	20	93.3	22
400	88.6	23	92.3	26

The HE/LC case reduces electricity to 85.2% of the BAU case and fossil fuel to 92.5%. The energy/carbon savings in the table would be larger if these higher prices systematically affect the penetration rates of new technology, which one would expect. However, penetration rates are currently parametric in LIEF, and since we have very little information about how price changes affect penetration rates, we have not altered that parameter for this exercise. Given the belief that the rise in prices would increase penetration, the estimates of energy and carbon savings from LIEF would represent an upper bound on the required carbon tax or a lower bound on the savings.

The implications of the 'standalone' analysis of carbon shadow prices is that a variety of polices well beyond a carbon permit charge would be required to achieve the savings projected in these scenarios.

4.3 ADDITIONAL EMISSIONS REDUCTIONS FROM INDUSTRIAL LOW-CARBON TECHNOLOGIES

4.3.1 Introduction and Summary

Industrial low-carbon technologies reduce greenhouse gas emissions through means other than traditional energy efficiency. We separate low-carbon technologies into three types:

- *Power-system efficiency maximization* (PSEM) technologies: such technology systems comprise mainly existing technologies assembled in an innovative way so as to maximize energy efficiency at certain types of locations for particular industries' heat and power needs.

- *Fuel-switching* technologies: these reduce carbon emissions by using low- or no-carbon fuels instead of high-carbon fuels. Many energy forecasting models, including LIEF and NEMS, incorporate switching from oil, coal or electricity to less carbon-intensive gas. They do not, however, generally incorporate switching to new advanced biomass or other new renewable technologies. Both of these low-carbon technology types are often grouped with energy-efficiency technologies. We separate them from efficiency technologies in this chapter because their additional contributions to carbon reductions are not generally included in traditional energy models.

- *Low process carbon* technologies: this type reduces or avoids the emission of CO_2 and other greenhouse gases from industrial processes, not from combustion. They are clearly not included in energy models. We have found that most of these emissions are non-CO_2 greenhouse gases. Because these emissions do not involve energy, they have not been included in energy-focused carbon analyses. However, as shown in Section 4.3.4, these non-energy emissions account for a third of total greenhouse gas equivalent emissions in the industrial sector. (Industrial CO_2 emissions from energy are projected to be 482 MtC equivalent in 1997 (EIA 1996) and non-energy-related carbon equivalent emissions were 244 MtC equivalent in 1994).

This section provides examples, rather than a comprehensive survey, of low-carbon technologies. Such a survey would have been difficult because, unlike traditional energy-efficiency technologies, these technologies do not have a long history of being analyzed from the perspective of reducing carbon equivalent emissions. However, as shown in Table 4.11, just these examples showed great potential reductions. Thus, a comprehensive survey of these technologies is an important area for future analysis in the industrial sector. Note that the carbon reductions presented are in addition to the carbon savings of Section 4.2.2. Some of these technologies also feature carbon reductions due to traditional energy efficiency. We used the energy-efficiency projections for the various traditional markets presented in Section 4.2.2 to subtract these carbon savings from the technologies' estimated overall carbon reduction. Greenhouse reductions from "low process carbon" technologies are not included in this report's summary tally of carbon reduction potential because of the report's focus on combustion-related emissions.

In the following sections, we provide examples of the three types of low-carbon industrial technologies. The Advanced Turbine System (ATS) described in Section 4.3.2 is an example of a PSEM technology. It is a combined heat and power (CHP) system that replaces grid electricity and steam from industrial boilers with a highly efficient on-site natural gas-fired turbine that generates both electricity and steam. The carbon reductions from on-site CHP were not included in Section 4.2.2. The ATS may also further maximize system efficiency by replacing electricity used to drive motors that drive equipment with direct power for the equipment. Even when used as a power-only technology, ATS reduces carbon emissions because it is located on-site – avoiding transmission and distribution

(T&D) losses. The ATS is also a fuel-switching technology if it replaces high-carbon fuels such as coal used in the boilers with natural gas or no-carbon biomass gas.

Section 4.3.3 gives an example of a fuel-switching technology. Black liquor and biomass gasifiers integrated with combustion turbines replace biomass boilers and grid electricity. In the near and medium time frame, biomass and black liquor gasification technologies provide the option of switching from a high-carbon to a "no-carbon" fuel. Note that the advanced technologies described in Section 4.3.3 are also PSEM technologies because they replace inefficient biomass boilers and grid electricity with biomass gasification combined heat and power systems.

Section 4.3.4 describes two low process carbon technologies. The first, the advanced aluminum production cell, shows that for some industrial processes there are multiple opportunities for reducing carbon equivalent emissions. The second involves the substitution of waste products – fly ash and blast furnace slag – for a portion of the calcined cement clinker intermediate product in cement production. Both of the examples reduce carbon through improved energy efficiency in addition to reducing or eliminating carbon equivalent process emissions.

A summary of the carbon reductions from these technologies is given in Table 4.11 for both the efficiency and the high-efficiency/low-carbon (HE/LC) cases.

Table 4.11 Examples of Additional Carbon Equivalent Reductions by 2010 Resulting From Low-Carbon Technologies* (MtC equivalent)

	Efficiency Case	High-Efficiency/Low-Carbon Case
Power System Efficiency Maximization Technology (PSEM)		
Advanced Turbine Systems	5-7	14-24
Fuel-Switching Technology		
Forest Products – IGCC	5	10
Low Process Carbon Technologies		
New Aluminum Production Cell	0–1	2–4
Cement Clinker Replacement	-	1–2
Total	**10–13**	**27-40**

*These reductions are not accounted for in Section 4.2.2.

4.3.2 Power System Efficiency Maximization Technologies

Power-system efficiency maximization technologies are grounded in the second law of thermodynamics. PSEM technologies take advantage of the fact that waste heat is always produced. Such systems also reduce or avoid extra energy conversion and process steps that waste energy. The key to PSEM is the system. Instead of using a separate technology for electricity for the company's PCs, building heating and cooling, process steam and electricity for motors, a company could use a PSEM technology. For example, the Advanced Turbine System (ATS) described in Section 4.3.2.1, could provide all these system needs. The ATS could provide reliable high-quality electricity to the PCs; ATS steam coupled with a heat exchanger could provide building heating and cooling and steam for process uses; and the turbine could be hooked directly to the drive shaft of the machine formerly driven by a motor that used grid electricity. District energy sites, where businesses group together and share electricity and steam from the same turbine, are also examples of PSEM technologies in the industrial sector. A recent study (IDEA 1997) indicates that, of the nearly 6000 current U.S. district heating installations generating more than 1.1 quads, 8% are classified as industrial. We expect that well-crafted policies to increase energy efficiency and reduce carbon will spur creative uses of both heat and power in such systems. In addition to multiple incremental improvements, we expect that some PSEM will be breakthrough technologies.

4.3.2.1 Advanced Turbine Systems (ATS) for Industrial Applications

Advanced Turbine Systems (ATS) are high-efficiency, next-generation gas turbines that produce less carbon per kWh than technologies used in conventional power markets. When commercialized in the year 2001, the emissions of CO_2 from ATS are projected to be 600 lb/MWh, 29–73% lower than conventional technologies (see Figure 4.3).[9] ATS is one of the major low-carbon technologies for the industrial sector between now and 2010 because it is a natural gas-fired turbine that cogenerates electricity and steam. The ATS's high energy efficiency stems from multiple incremental improvements applied in a novel manner.[10] Cogenerated steam displaces industrial steam boilers and their associated emissions. The steam can also be put back into the system for additional electricity generation. Further emissions reductions are due to the ATS being gas-fired and located on-site.

Although not included here because of possible double counting with Section 4.3.3.1, the ATS technology is also well suited for biomass and landfill gas fuels. The ability of ATS to burn biomass without turbine fouling and maintenance problems is being explored via new turbine materials, including ceramics and single crystal and directionally solidified turbine blades. Substantial reductions in greenhouse gas emissions will result if ATS is fired with biomass fuel – especially in combined heat and power mode. It will require the evolution of a biomass fuel supply infrastructure, or its penetration will be limited to those industries that already have access to biomass fuels, such as forest products and some food processing sectors. We provide an example of biomass-based cogeneration in the paper industry in Section 4.3.3.

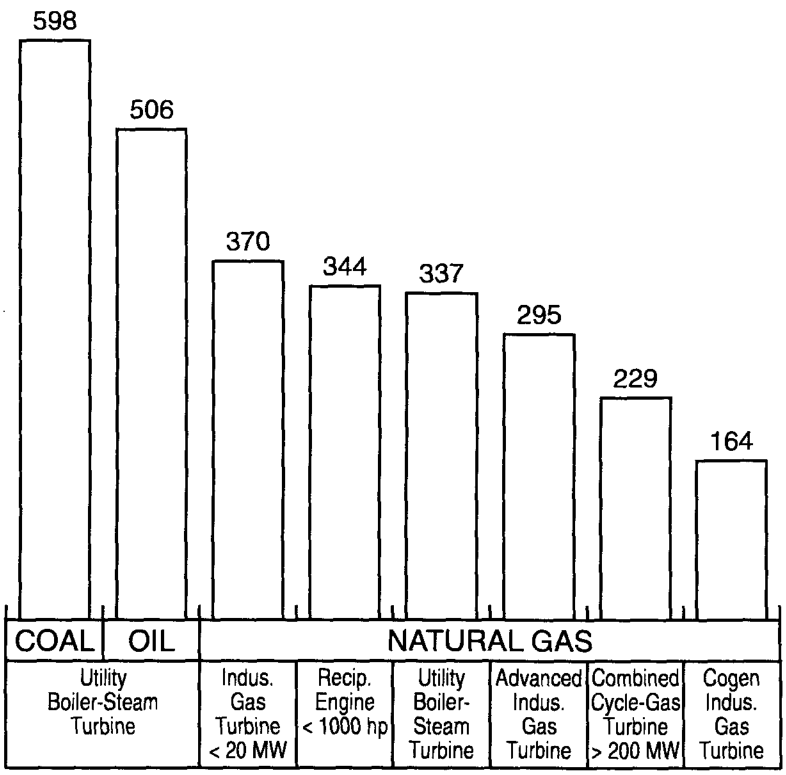
We divided the ATS "markets" into three types. The first type includes high electricity-to-thermal (E/T) ratio "power only" opportunities. These are sites where there is little or no steam demand and most of the steam from the ATS is fed back into electricity generation. The second type, "combined heat and power" (CHP), includes sites where ATS provides both steam and electricity needed on-site. The third type is a "new steam" market, where the steam and electricity needs vary.[11]

This "new steam" market is a new market not included in most energy forecasting models. It is new CHP capacity in which power and heat are not balanced and where the desire to generate electricity may be more important than getting the perfect steam match. Unlike traditional cogeneration equipment that is only efficient at a particular E/T ratio, ATS CHP systems run at high efficiency in a variety of steam and electricity configurations. As detailed in Appendix D-3, this market will spur creative uses of both heat and power. For analytic purposes, we have analyzed the "new steam" market as if it were two separate CHP and power-only markets. We decomposed new steam into traditional CHP (cogeneration assuming heat/power balance) and Power-Only (PO):

$$\textit{New steam} = a^*CHP + b^*PO$$

While some sector-specific studies (Appendix D-3) show a and b values around 0.5 for the entire market, the values of a and b are not well known except that they are both significant. As detailed in Appendix D-3, this decomposition also simplifies the calculation of the carbon offset. Figure 4.4 depicts simplified diagrams that allow comparison of the following: (1) a traditional steam boiler system, (2) a steam boiler that produces power using an ATS, (3) an ATS used for combined heat and power, and (4) an ATS used for power only. There are many other combinations, such as a turbine with a recuperator not shown here.[12]

Figure 4.3 Carbon Equivalent Emissions for Several Electric Generation Technologies (pounds per MWh)



Source: Gas Research Institute (1994) and Onsite Energy (1997)

Considering the large markets not yet served by this type of CHP, industry experts predict that the availability of advanced turbines will double the growth rate of new CHP capacity (Carroll 1997). This growth will greatly exceed the historic industrial market penetration of cogeneration,[13] particularly for smaller power technologies used to meet internal energy requirements. Under the efficiency or high-efficiency/low-carbon scenarios, the change in the market will occur even faster. Relatively higher prices for carbon-based fuels will encourage dispatching of electricity from low-carbon fuels, reform of environmental permitting, and utility regulations and will thus accelerate the replacement of boilers by on-site ATS cogeneration. The turbine's low installed costs, low NO_x emissions, and ability to generate electricity when steam is not needed will also contribute to the rapid growth of this new steam market.[14,15]

Table 4.12 shows the contributions of these two "markets" to the total carbon reductions. As described in Appendix D-3, the power-only carbon reductions are much smaller because we assume that the power being displaced is also quite efficient.[16] Thus, the ATS only takes credit for carbon reductions due to avoidance of transmission and distribution losses (7%). In addition, we assume the grid electricity (see utility chapter for details) and the steam boilers displaced have higher carbon emissions than those displaced in the efficiency case. For both cases, we subtracted the same traditional cogeneration that is contained in the NEMS BAU.

Figure 4.4 Simplified Diagrams of Advanced Turbine Systems in Power-Only and Cogeneration Mode Compared to Steam Boiler

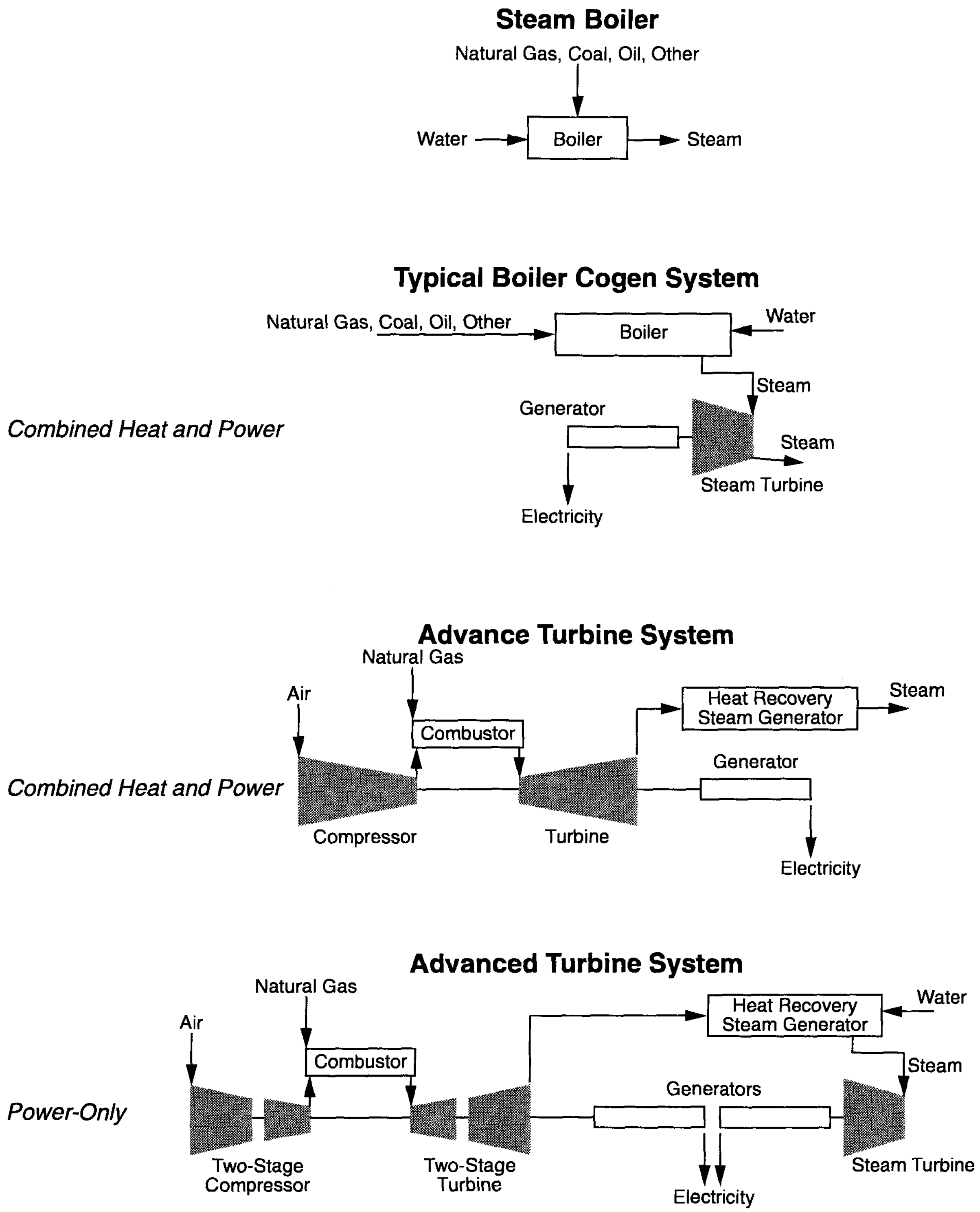


Table 4.12 Calculation of 2010 ATS Carbon Savings (MtC) and Corresponding ATS Electricity Generation (TWh)**

	Combined Heat and Power*	Power Only	Total
Efficiency	4-6 (29-59)	1 (120)	5-7 (150-180)
High-Efficiency/Low-carbon	12-21 (60-120)	2 (220)	14-24 (280-340)

Numbers may not add up exactly due to rounding. TWh shown above in parentheses.

* Excludes carbon reductions and electricity generation from traditional cogeneration that is contained in the NEMs BAU case as well as forest products biomass cogeneration which is considered in Section 4.3.3. Other ATS markets where ATS electricity generation did not result in substantial carbon savings were also excluded.

** See Table D.3-4 for details.

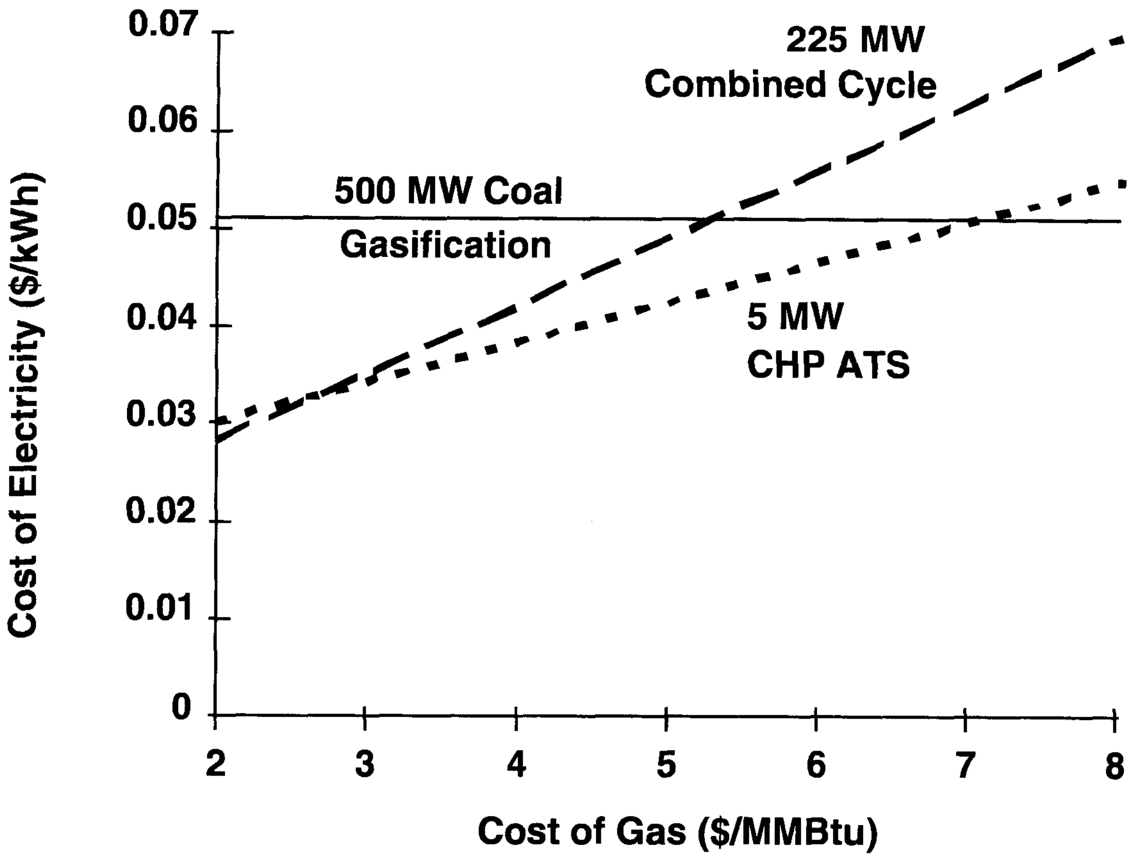
We estimate ATS carbon reductions of 5-7 MtC equivalent for the efficiency case (see Appendix D-3). This corresponds to an electric capacity of 23-27 GW and requires 0.5 TCF of additional natural gas (5% of 2010 BAU industrial demand) due to fuel switching from oil and coal biolers. For the high-efficiency/low-carbon (HE/LC) case we assume, similar to Section 4.2.2, that the penetration of ATS in these markets will double over that of the efficiency scenario. In addition, we assume the grid electricity (see utility chapter for details) and the steam boilers displaced have higher carbon emissions than those displaced in the efficiency case. This results in an ATS HE/LC carbon reduction of 14-24 MtC equivalent per year by 2010. This corresponds to an electric capacity of 42-51 GW and 1.0 TCF of additional natural gas (11% of projected BAU 2010 industrial demand).

Most of the carbon reduction comes from the fact that the ATS has a combined efficiency that is 5-10% greater than boilers. This greater efficiency also results in electricity costs that are 10% lower than current generation systems. Equipment costs are projected to be approximately $350/kW ($1.8M for a 5 MW unit) for a recuperated simple cycle unit and somewhat higher for a combined cycle unit. The major turbine manufacturers in the U.S. project that ATS will have captured 15% of U.S. power generating capacity by 2010 (Major 1997). In power-only mode, the system will be competitive against electricity prices of $0.03-0.04/kWh (Brent and Davidson 1996, Hoffman 1997). More specifically, Figure 4.5 shows that the ATS is the least-cost option for a wide range of gas and electricity prices, but it does not compete favorably with very low gas prices (where the large combined cycle turbine is less expensive) or with high gas prices (where coal gasification systems are less expensive). Note that the breakeven point between ATS and combined cycle systems is very close to the projected price of natural gas to industrial consumers ($2.60 per million Btu) in the AEO97 BAU case.

Even though the ATS is 2-3 years from being commercialized, some of the ATS manufacturers already have significant orders for ATS (Parks 1997). Since the average order/delivery time is 18 months, this means that the ATS customers are willing to wait at least 18 additional months for a superior technology. This suggests that the ATS may penetrate far more rapidly than traditional energy technologies.

In addition to carbon reduction, these turbines have other environmental benefits. ATS's low-emission combustion systems generate less than 9 ppm NOx through lean premix combustion and less than 5 ppm NOx with catalytic combustion, with no other major pollutants. When deployed in 2001, ATS systems, per MW, will produce 77–95% less NOx per megawatt than competing power generation technologies (Major and Davidson 1997b).

Figure 4.5 Electric Generation Cost Comparison



Source: Onsite Energy (1994)

4.3.3 Fuel-Switching Technologies

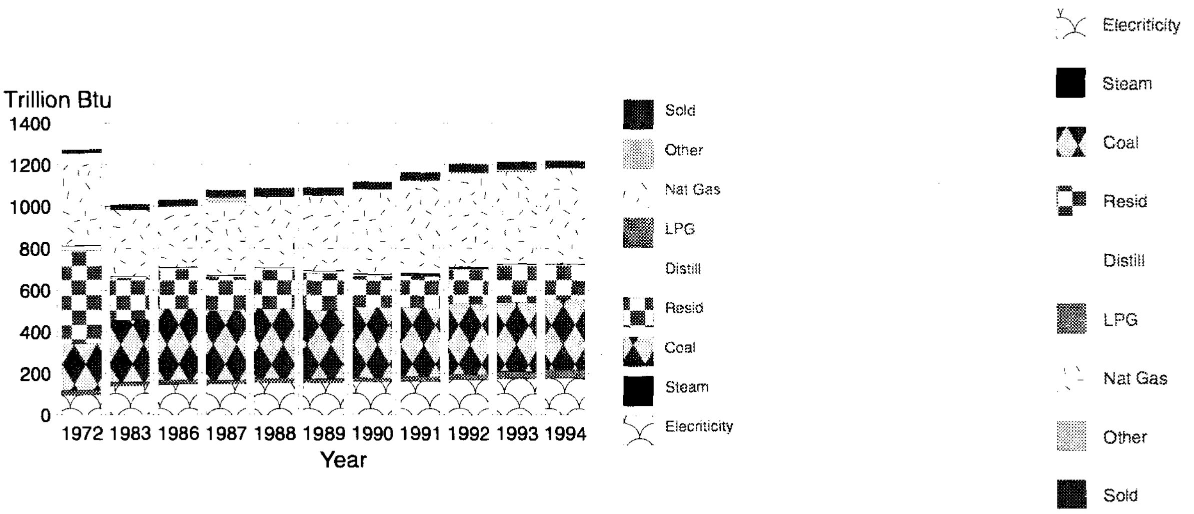
In the very near-term, fuel switching from high-carbon fuels such as coal to lower-carbon fuels such as natural gas is feasible and is already included in most energy forecasting models. In the near and medium time frame, biomass and black liquor gasification technologies described in Section 4.3.3.1 provide the option of switching from a high-carbon to a "no-carbon" fuel. Biomass is considered "no-carbon" because we assume the CO_2 produced will be rapidly resequestered by growing biomass feed stock (see Chapter 7 for more detail on biomass). These technologies can also be considered PSEM technologies because they replace inefficient biomass boilers and grid electricity with biomass gasification cogeneration. Black liquor technology utilizes black liquor gasification instead of improved efficiency recovery boilers (which are the replacements implicit in the modeling calculations of Section 4.2.2). Biomass gasifiers replace inefficient boilers for steam and electricity. These technologies allow the industry to generate more of its own electricity which leads to the offset of purchased electricity. The extra generation of biomass-based electricity is not included in the modeling calculations of Section 4.2.2 and is responsible for the carbon offsets calculated here. Although no examples are provided, other renewable energy-powered industrial technologies (e.g., solar detoxification) could also be considered low-carbon fuel-switching technologies.

4.3.3.1 Integrated Gasification Combined Cycle Technology for the Forest Products Industry

Integrated gasification combined cycle (IGCC) technologies can significantly impact the carbon reductions expected in the forest products industry in two ways: (1) by increasing energy self-generation and (2) by better utilizing residues from the forest management and manufacturing processes. Potential offsets of carbon emissions by 2010 are approximately ten MtC equivalent per year in the high-efficiency/low-carbon scenario. The efficiency scenario could achieve offsets of about 5 MtC equivalent per year. To achieve the carbon reductions in the high-efficiency/low-carbon scenario, it will be necessary to facilitate early commercialization to reduce investment risk and provide an incentive for industry to commit the resources necessary to implement these advanced technologies.

The pulp and paper industry purchases 43% of its energy and uses a diverse mix of resources including electricity, steam, coal, residual and distillate fuel oil, liquid propane gas, and natural gas. In 1972, the industry used oil for nearly a quarter of its purchased energy but this proportion decreased to 6.9% in 1994 by doubling purchased electricity and increasing coal purchases by 50%. This complex purchased fossil fuel and energy pattern is shown in Figure 4.6.

Figure 4.6 Purchased Energy in the U.S. Pulp and Paper Industry by Fuel Type, 1972–1994



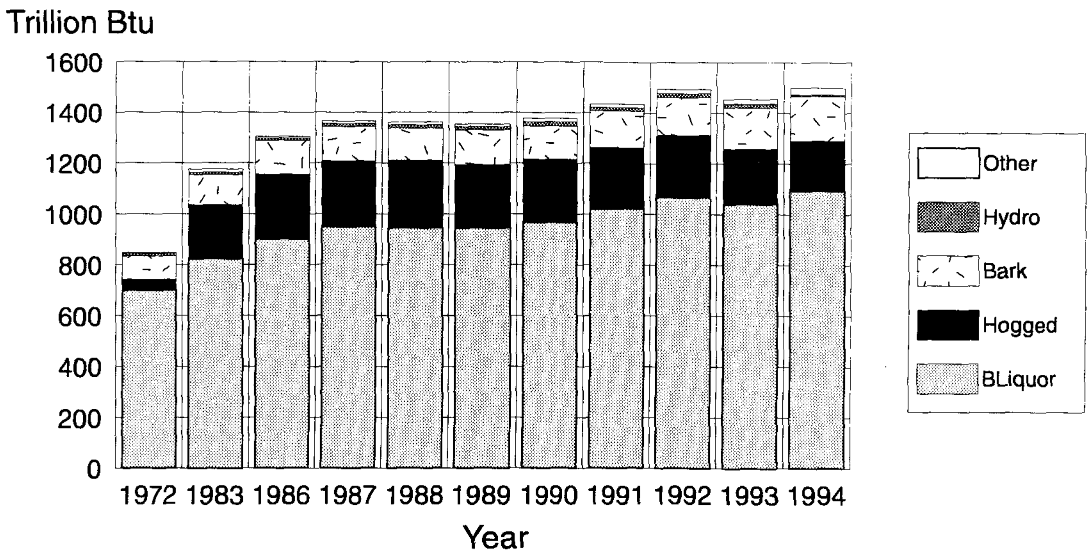
Source: Miller Freeman, Inc. (1972–1994)

The industry self-generates the remaining 57% of its required energy through the recovery of energy and chemicals in spent black liquor, use of residues such as hog fuel and bark in boilers, and cogeneration of heat and power (see Figure 4.7). The American Forest and Paper Association (AF&PA) estimates that use of these energy sources displaced more than 227 million of barrels of oil in 1994 (Miller Freeman, Inc. 1996).

These fuel switches, increased cogeneration, and energy conservation measures resulted in a decrease in energy intensity. Even though total energy consumption increased over the period 1972–1994, energy consumption per ton of product output decreased by 21% (Miller Freeman, Inc. 1997).

Two opportunities for further improvements were analyzed in detail: increased self-generation from black liquor and increased recovery of usable energy from hog fuels and bark coupled with increased recovery of forest residues and pre-commercial thinnings. Increased self-generation offsets purchases of electricity and coal, and thus offsets CO_2 emissions.[17] These higher-efficiency processes could also increase the industry's electricity production for return to the grid.

Figure 4.7 Self-Generated Energy in the U.S. Pulp and Paper Industry by Fuel Type, 1972–1994



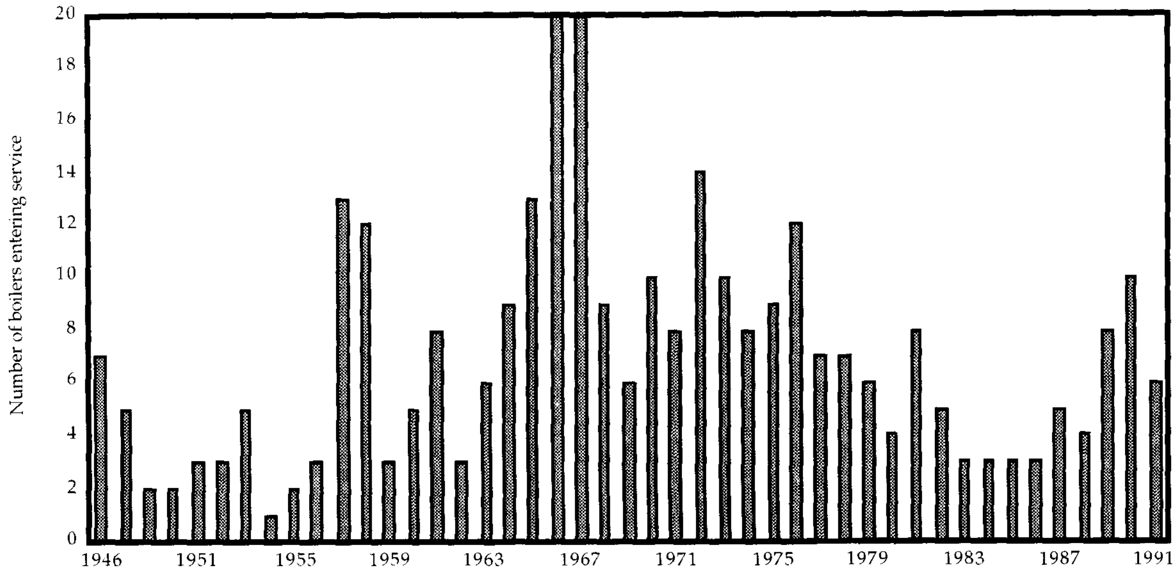
Source: Miller Freeman, Inc. (1972–1994)

Kraft Recovery Boiler Replacements. Traditionally, about 40% of the energy used in a mill is generated from burning the lignin solids. Lignin is the portion of wood that holds the fibers together and makes them stiff. The pulping process separates the lignin from the pulp fiber. The lignin is a dilute solution which is evaporated and burned in a boiler designed to recover the pulping chemicals; heat from combustion is used to make steam. Some of the steam is used to supply the mill's needs and some is used to generate electricity for the mill.

In the black liquor gasification combined cycle process, a little less steam is generated but two to three times more electricity is produced. Process changes designed to make mills more environmentally friendly tend to change the balance of energy forms that a mill uses. Mills are using less steam energy and more electrical energy; the combined cycle process fits right into the future process needs.

The technology is coming on the scene at an opportune time because most of the existing recovery boilers in the industry are reaching the end of their useful safe operating life. The majority of recovery boilers were put into service between 1955 and 1980, with a peak period around 1967 (see Figure 4.8). For environmental and safety reasons the industry is developing alternative technologies in anticipation of replacing these boilers after a 40-year service life. The need for capital replacement creates an opportunity for penetration of new, high-performance, environmentally acceptable technologies. The gasification component of the replacement technology is already at the early stages of commercial deployment, mainly as a means of expanding mill electric generation capacity in situations where the current recovery boiler limits throughput. There is a need for chemicals recovery cycles to be tested and for the integrated cycle to be demonstrated. Expediting RD&D could allow significant carbon emissions offsets by matching the timing of technology development and commercialization to the need for boiler replacement.

Figure 4.8 Kraft Boilers in Service in the United States



Source: American Forest and Paper Association

A major barrier to the adoption of black liquor IGCC systems is the central role that the current recovery boiler plays in the chemical and energy recovery of the mills. Typically, this part of the pulping process has to reliably operate at full throughput with annual capacity factors of greater than 95%. A further barrier is the need for process heat. Increasing the electricity output will require a concomitant improvement in process heat utilization since the steam output of the black liquor IGCC system will be 21% less than that of the recovery boiler, even though the electricity output is effectively doubled.

Replacement of the current recovery boilers by new technology based on gasification to recover both process chemicals and the energy content of the dissolved lignin has the potential to produce 104 TWh of electricity per year, offsetting about 100 Mt of CO_2 emissions. Full replacement of the current recovery boiler capacity at the 1996 production volume would offset 26 MtC equivalent per year. Based on a rate of recovery boiler replacement that assumes a 40-year life for the existing recovery boilers, the 2010 displacement is 5.2 MtC equivalent per year, and the 2020 displacement is 8.7 MtC equivalent per year. The methodology used to determine the replacement rate, on which the projected carbon reductions are based, is discussed in Appendix D-4. The black liquor IGCC system is designed to meet New Source Performance Standards (NSPS), and would also have low NO_x and SO_x emissions. Investment costs for integrated gasification combined cycle are forecast to be less than those for replacement with a conventional recovery boiler system, on a dollar per kilowatt-hour basis. It is anticipated that IGCC systems would be competitive against electricity purchases at $35/MWh.

Residual Biomass Boiler Replacements. Food processing, wood products, and pulp and paper are industries that generate large amounts of residual biomass (e.g., waste wood and bark). While much of this biomass is currently being used, if it were gasified and used to cogenerate steam and electricity, it would substitute for (largely) fossil fuel-produced electricity. Advances in turbine efficiency (see Section 4.3.2.1) make this an economically attractive option. By using residues from pulping processes as well as biomass from forestry operations in conjunction with gasification and combined cycle technologies, 2.3 GW of capacity can be put in place by 2010, offsetting 4.8 MtC equivalent per year. This would represent about one-third of the potential mill conversions projected to need replacement by that time. Because of the stage of development of the technology and its markets, a conservative estimate would reduce replacements from one-third to one-quarter of the potential mill conversions. Using the more conservative penetration, the carbon replacement potential from gasification of residual biomass is 3.6 MtC equivalent per year.

Approximately 200 mills are already producing heat and some power from the use of residual biomass in their processes.[18] The majority of in-place boiler units entered service between 1965 and 1975 and need replacement; they are either reaching the end of their service lives or they may have difficulty meeting environmental regulations (or both). Residual biomass gasification can penetrate this replacement market with the potential to double the net rate of electricity generation – from a generation efficiency of about 15% to 35%. The technology is already in the early stages of commercialization with the first 18 MW IGCC operating in Sweden. Prototype units are being demonstrated elsewhere in Scandinavia and the United States.

The current cost of this technology is approximately 50% over the plant cost when the technology is mature. Incentives will be necessary to facilitate entry of the technology into the replacement market. One proposal is a capital cost buydown to bring technology costs down.

The gasification system is designed to meet New Source Performance Standards (NSPS) and would have low NO_X and SO_X emissions. Biomass growth and harvesting would be according to best practices, and to some extent the biomass fuel source could include materials that are currently landfilled and thus contribute to landfill methane emissions.

4.3.4 Low Process Carbon Technologies

Low-process carbon technologies reduce or avoid the emission of non-combustion CO_2 and other greenhouse gases in industrial and other processes. As shown in Table 4.13, 92% of the carbon equivalent emissions of process carbon are due to non-CO_2 greenhouse gases that have far higher global warming potentials (GWP) than CO_2.

4.3.4.1 Industrial Sources of Non-CO_2 Greenhouse Gasses

Although non-CO_2 industrial emissions of greenhouse gasses are small by weight, they have GWPs that range from 21 for methane to 23,900 for sulfur hexafloride (SF_6). Figure 4.9 shows the relative contribution of these other gases in MtC equivalent. The largest non-CO_2 greenhouse gas contribution is from methane (CH_4), which is responsible for 177.5 MtC equivalent and has a GWP of 21. Next is nitrous oxide (N_2O) which is responsible for 39.1 MtC equivalent and has a GWP of 310. Finally, in 1994, various halocarbons and other engineered chemicals amounted to 29.5 MtC equivalent. These engineered chemicals are a source of concern since their emissions are growing rapidly – and the United States is the major source. As shown in Table 4.13, emissions of these other greenhouse gases from agriculture (27%), mining/energy extraction (25%), service (24%), and transportation (8%) sectors are important.

The manufacturing sector accounts for 14% of carbon equivalent emissions due to other greenhouse gases. The manufacturing processes that generate GHG emissions include:

- Waste emissions of CF_4, C_2F_6, C_3F_8, NF_3, and CHF_3 from plasma etching, chemical vapor deposition (CVD), and CVD chamber cleaning in semiconductor manufacturing;

- Waste emissions of SF_6 from the manufacture of transformers, circuit breakers/load-shedding devices, and electrical distribution components where SF_6 is used as an insulator;
- By-product emissions of N_2O from adipic acid manufacture;[19]
- Waste methane emissions from production of ethylene and styrene;
- PFC emissions from aluminum production (see Section 4.3.4.3); and
- Waste emissions of SF_6 from magnesium casting in which SF_6 is used as a cover gas to protect against catastrophic oxidation.

Table 4.13 Process Carbon Emissions and Energy Use by Sector

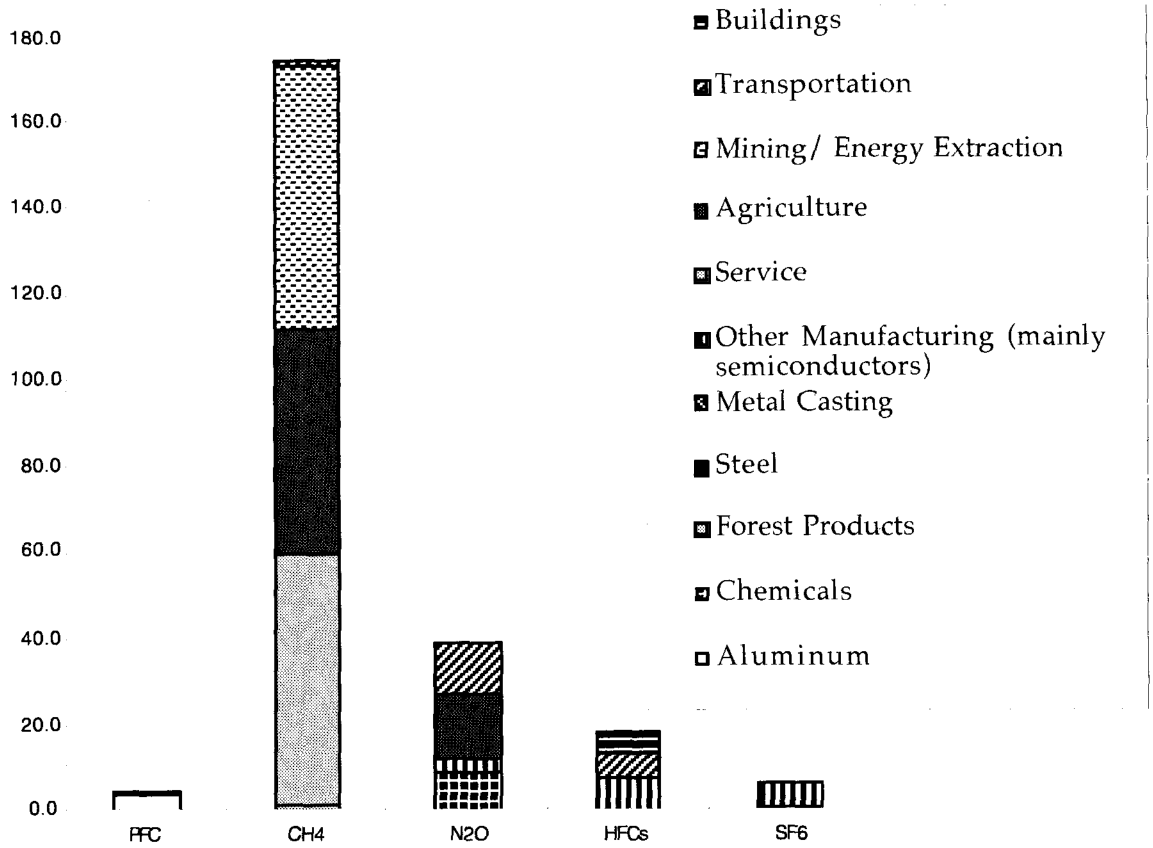
	Carbon Emissions (MtC equivalent)			
	Process CO_2*	**Other GHG Carbon Equivalent**	**Total Carbon**	**Energy Use (quads)**
Manufacturing	18.4	33.0	51.4	22.4
Service	0	58.2	58.2	
Agriculture	0	66.7	66.7	
Mining/Energy Extraction	0.9**	61.5	62.4	
Construction	2.0	0	2.0	
Subtotal Industry	**21.3**	**219.4**	**240.7**	**32.6**
Buildings	0.0	5.3	5.3	33.7
Transportation	0.0	19.0	19.0	25.5
Total	**21.3**	**243.7**	**265.0**	**91.8**

*Source: EIA 1996

**Gas flaring.

While none of the manufacturing emissions are particularly large, we note that global emissions of SF_6 are increasing at a rate of 7–8% per year. This is of particular concern because SF_6 has a very high global warming potential of 23,900 and an expected lifetime of 3,200 years, making it a very potent greenhouse gas. Thus SF_6 emissions alone are increasing at a rate of 0.5 MtC equivalent per year (EIA 1996). Several emerging technologies may be immediately helpful in avoiding these emissions. For example, applications of high temperature superconductor technologies include transformers and current limiters that act as circuit breakers (Platt 1997). Many of these emissions are seen not only in energy-intensive industries but also in "high-tech" manufacturing industries. These non-energy-intensive industries include semiconductor manufacturing and equipment manufacturing for the electric utility industry. Due to scope and time constraints, technology options to reduce these emissions are not addressed in this report but are an important area for future analysis.

Figure 4.9 Non-CO_2 Greenhouse Gas Emissions in the United States (MtC equivalent)



Source: EIA (1996)

4.3.4.2 Process CO_2 Emissions

Compared to other greenhouse gases, process CO_2 emissions are relatively small, accounting for only 9% of process carbon emissions and less than 5% of industrial combustion-related CO_2 emissions. Overall, the industrial sector directly emitted about 23 MtC from CO_2 industrial processes.

The primary industrial processes that generate process carbon emissions include:

- The calcination of limestone in cement manufacture (largest single source);
- The manufacture and consumption of limestone (e.g., in lime kilns, iron smelting, steel making, glass manufacture and flue gas desulfurization);
- Dolomite consumption;
- Soda ash manufacture and consumption (e.g., in glass manufacture, flue gas desulfurization, and chemicals production);
- CO_2 manufacture;

- Gas flaring; and
- Aluminum production.

There has also been a disproportionate increase in process CO_2 emissions relative to combustion-related CO_2 emissions. Over the past eight years, process CO_2 emissions have increased nearly 16% while combustion-related CO_2 emissions have increased only 4%. However, these process carbon data are highly uncertain due to their variability across sites due to non-uniform measurement technique. For example, the carbon emissions could be flat in reality but appearing to rise because measurements are more comprehensive today.

The following sections describe carbon savings in the aluminum and cement industries that are possible given aggressive RD&D and commercialization strategies.

4.3.4.3 Low-Carbon Technologies in Primary Aluminum Production

Because of the very high chemical stability of aluminum oxide and other aluminum compounds, the production of aluminum metal was not feasible until the nineteenth century when electrical power generation facilities became available to permit commercial electrolytic reduction operations. Creation of today's world-wide aluminum industry occurred after the simultaneous inventions by Hall and Heroult of a process for high-temperature reduction of aluminum oxide dissolved in a molten fluoride salt using a carbon anode which is consumed during the process reacting to form carbon dioxide.

The global warming potential associated with aluminum production results from several factors

- First, carbon dioxide is generated at fossil fuel plants that produce the electricity required for the electrolysis process.[20] State-of-the-art Hall-Heroult cells achieve power consumption levels as low as 13,200 kWh/tonne of aluminum produced; however, most aluminum plants require more electricity per tonne of product.
- Second, the production of one metric ton (or tonne) of aluminum leads to the generation of at least 1.22 tonnes of process carbon dioxide (or 0.33 tonnes of carbon) from the reduction cell operation.
- Third, global warming effects also result from the generation of perfluorocarbons (CF_4 and C_2F_6) during instabilities in the cell operation (called "anode effects") that occur when oxide concentration in the cell bath becomes undesirably low. In 1994, aluminum smelting is estimated to have emitted the equivalent of 4.2 million metric tons of carbon equivalent, from perfluorocarbon (PFC) byproducts (EIA 1996).

Further reductions in the levels of greenhouse gas emissions associated with primary aluminum production will require:

1. Development of reduction technologies that require less energy for primary metal production;
2. The development of inert, non-carbonaceous anodes that are not consumed through the reduction process; and
3. The development of improved cell designs and operating control strategies to reduce PFC emissions.

On the basis of ongoing research on aluminum reduction technology, the desired improvements will require the development and commercialization of retrofit advanced cell technology with wettable cathode and inert anode components. Two scenarios have been developed: an efficiency scenario, based on the development and use of wettable cathodes with conventional carbon anodes, and a high-efficiency/low-carbon scenario, based on the addition of inert anodes to the advanced cell.

Under both the efficiency and high-efficiency/low-carbon scenarios, R&D on advanced aluminum production cells would be funded by both the federal government and the private sector. However, under the high-efficiency/low-carbon scenario, the development of inert anodes and the associated control systems would be pursued more aggressively. In either case, alternative cathode and anode materials, advanced cell designs, and advanced operating control methods would be developed with the overall goal of reducing the cell voltage (electrical energy requirements and associated power plant CO_2 emissions), eliminating CO_2 cell emissions, and significantly reducing emissions of PFCs arising from cell operating instabilities. In the discussion below, we analyze the incremental energy efficiency improvements and reduced carbon gas emission savings from these advanced low-carbon technologies for primary aluminum production.

Under the efficiency scenario, the wettable cathode part of the advanced cell is forecast to be ready for commercial operations by approximately 2005. Conventional, non-wettable cathode cells operate with thick metal layers above the cathode surface. In contrast, use of wettable cathodes permits cell designs in which product metal can be drained from the cathode to collection sites within the cell leaving only a thin film of metal at the cathode surface. Normal undulations at the metal surface resulting from electromagnetic stirring and gas bubble driven circulation are virtually eliminated with wettable cathodes permitting cell operations with reduced anode-cathode spacings. In combination with advanced process sensors and control systems to optimize cell operation, the potential energy savings are estimated to be as high as 15–20% over conventional cells (DOE 1990). These same sensors and control systems would yield reduced levels of PFC gas emissions. These technologies will be designed for simultaneous or independent retrofit use on existing cells.

The high-efficiency/low-carbon scenario forecasts the additional development of inert anodes. The most promising materials presently being evaluated are ceramic/metal composites consisting primarily of nickel oxide and nickel ferrite with a copper/nickel metal phase (Windisch and Strachan 1991). These permanent anodes would also eliminate CO_2 emissions associated with the manufacture and consumption of carbon anodes. If successful, the advanced cell would result in an approximate 27% reduction in the electricity requirements for primary aluminum production.

Research would be scheduled so that commercial-scale demonstration tests (individual commercial sized reduction cells up to the actual conversion of an operating potline) would be in operation by approximately 2005. To re-engineer an existing smelter site with radically different production may require a capital investment ranging from $500,000 to $2 billion. For investments of this scale, conclusive demonstrations defining operating performance, operating costs, and equipment lives must be completed to achieve industry acceptance and widespread adoption.

The economic feasibility of the advanced technology would be enhanced if federal policies promoting further reductions in carbon emissions were established. Even without such policies, the U.S. aluminum industry has expressed a goal of eliminating process CO_2 emissions in primary aluminum (Energetics 1997). Furthermore, trends toward increased use of aluminum in the transportation sector to improve vehicle fuel efficiency through weight reduction could significantly increase demand for primary aluminum, further increasing the economic feasibility of the advanced cell technology.

Under the efficiency scenario, we assume that five of the existing 22 aluminum plants operating in the U.S. (American Metal Market 1997) are retrofitted to use the advanced wettable cathode cell. With an average plant capacity of 190,000 tonnes of aluminum per year and an average annual electricity consumption of 13,200 kWh per tonne of aluminum, electricity efficiency improvements of 17% in these five plants would result in 0.19 million tonnes of reduced carbon-equivalent emissions in 2010.[21] This is 0.09 MtC more than the efficiency scenario described in Section 4.2.2.[22] In addition, the PFC emissions from anode effects are projected to be halved in those five plants where wettable cathodes are installed. This would represent an 11.4% (or 0.48 MtC) reduction in the aluminum industry's carbon equivalent emissions of 4.2 MtC.[23]

Under the high-efficiency/low-carbon scenario, use of the advanced, inert anode by 10 of 22 plants could lead to reduced carbon emissions by 1.6 MtC equivalent, of which 1.00 metric tonnes of carbon savings are due to the reduced consumption of electricity.[24] This is equivalent to 0.67 MtC over the high-efficiency/low-carbon scenario described in Section 4.2.2.[25] An additional 0.6 Mt of carbon savings result from the elimination of carbon emissions from the production cell.[26] The use of inert anodes to eliminate the process CO_2 emissions from smelting was not considered in Section 4.2.2; thus, all of these carbon reductions are accounted for here. In addition, the PFC emissions from anode effects are projected to be eliminated in those 10 plants where inert anodes are installed. This would represent a 45.5% (or 1.91 MtC) reduction in the aluminum industry's carbon equivalent emissions of 4.2 MtC.[27]

These carbon reduction estimates are summarized in Table 4.14. The advanced aluminum production cell in the efficiency scenario accounts for 0.6 MtC (or 0.5 to 1.0 MtC) of reductions above the carbon reductions already incorporated in Section 4.2.2. The high-efficiency/low-carbon scenario accounts for 3.2 MtC (or 3 to 3.5 MtC) more than the carbon reductions already incorporated in Section 4.2.2. Technical details of the advanced aluminum production cell are discussed in Appendix D-6.

Table 4.14 Carbon Reductions from Advanced Aluminum Production Cells, in 2010 (MtC)

Sources of Carbon Reductions	Efficiency Scenario	High-Efficiency/Low-Carbon Scenario
Electricity Savings		
•Included in Section 4.2.2	0.1	0.3
•Increment above Section 4.2.2	0.1	0.7
Cell Production	0	0.6
Reduced Perfluorocarbons	0.5	1.9
Total	**0.7**	**3.5**

4.3.4.4 Replacing Cement Clinker with Solid Wastes

The cement industry is the single largest source of U.S. process CO_2 emissions and a major energy user. The annual process CO_2 emissions from the U.S. cement industry are 9–10 MtC equivalent (EIA 1996). Energy-related CO_2 emissions are of similar magnitude depending upon the cement kiln technology. Some estimates indicate that each ton of cement clinker produced results in the direct emission of one ton of CO_2. Other estimates with different kiln technologies have a much higher energy/process CO_2 ratio. Of the process emissions, about 60% of the direct emissions are from calcination of limestone and the other 40% are from combustion products from fossil fuels that directly or indirectly supply the energy for calcination.

Nearly all cement in the United States is made from ground clinker intermixed with gypsum. One technically straightforward and cost-saving way to reduce energy input and carbon emissions per ton of cement is to replace some of the clinker with abundant utility and steel plant wastes such as fly ash or granulated blast-furnace slag. Such a replacement makes cement with somewhat different properties, but still a satisfactory building material. Most European countries allow such cements and have found that these cements last longer and are more tolerant to salt water than pure clinker cement. However, U.S. product specifications (Standard Specification for Portland Cement, ASTM C150) do not allow any extra ingredients in cements. These specifications are difficult to change because the small minority of those who might lose markets (e.g., non-integrated cement producers) can easily stop changes under the current system. A recent study (Sauer 1997) estimates that changing the U.S. specifications to permit inter grinding could reduce both energy and process CO_2 emissions by 5–20% per year by reducing demand. If the specifications were changed, it is likely the new technology could be rapidly adopted by U.S. cement manufacturers, especially the multi-national firms that are already using this type of cement in Europe. Under the high-efficiency/low-carbon scenario, the barriers to this technology could be overcome. In addition, there would be motivation to conduct further research, development and demonstration activities exploring a wide range of cement inter grinding materials and percentages and to ensure that they provide the same or improved performance. Based on these studies and assuming a low-carbon, aggressive R&D scenario, our estimate is that by 2010, 1–2 MtC equivalent of industrial carbon emissions could be avoided due to cement inter grinding and replacement.[28]

Though the manufacturing process has remained the same, the U.S. cement industry has changed over the past 20 years. The number of kilns in operation has dropped by 50% since 1975. There has been a 28.3% improvement in fuel efficiency since 1975, dropping the energy required per metric ton of cement from an average of 7.26 MMBtu in 1975 to 5.20 MMBtu in 1994. Over 60% of U.S. clinker capacity is foreign owned or affiliated with foreign firms, and most of these are integrated European cement companies. The primary customer, accounting for 60% of shipments, is the ready-mix concrete industry which supplies concrete, mixed to customer specifications, to construction sites (Bureau of Mines 1994). Concrete typically contains 10–15% cement as a binder. Cement demand is projected to grow at 1% per year, half the rate of GDP.

On average, energy accounts for between 30 and 40% of cement manufacturing cost. Electricity represents about 10% of energy input, but frequently accounts for close to 50% of total energy cost. Integrated cement producers and ready-mix concrete suppliers would benefit from replacing high cost clinker with low- or negative-cost materials. The cement industry is already a leader in waste utilization. More than half of plants responding to a 1994 survey reported the use of one or more types of waste as fuel. This technology could, however, speed the decline of non-integrated cement producers.

In addition to reducing CO_2 emissions, this technique also reduces NOx, SO_2, and particulate emissions associated with electricity use. It also reduces solid waste by replacing quarried raw materials with wastes and by-products such as fly ash, foundry sands, and mine tailings.

4.4 PROVEN INDUSTRIAL TECHNOLOGIES

Although our forecasting methodology does not draw directly from detailed representation of individual technologies, the forecast savings that are expected in each sector will be drawn from a variety of sources of new technologies and business practices. This section illustrates the range of commercially available and near commercial innovations that firms in these industries can draw upon to achieve the additional reductions in energy use that are considered feasible in the HE/LC case and could contribute to this projected decline. In addition, we provide examples of technologies that directly displace carbon in Section 4.3.

We provide illustrative examples of currently-available technologies that we believe could be integrated into industry to provide the savings suggested by the model simulations for each energy-intensive industry; we also provide examples of cross-cutting technologies. We describe how each technology is used and from what type of efficiency it draws its energy and cost savings.

Some technologies recover or reduce the production of waste heat in high-temperature applications while others optimize the process load to the energy-using equipment. Many of the most successful technologies have multiple benefits, including pollution prevention or productivity-enhancing features. A technology that reduces product loss or increases process throughput will often reduce labor or material costs as well as energy costs. For example, continuous casting, widely adopted by the steel industry, is cost-effective based on its energy savings alone but industry has adopted continuous casters in large measure because of the improvement in steel quality and because it reduces losses. Similarly, impulse drying, an emerging technology, saves energy, but also allows additional throughput on the paper-making machines and will improve the quality of the product.

While it is felt that these technologies are representative and have the potential to be readily accepted by industry, the estimates of energy savings provided below *do not represent any industry consensus* of the relative difference between the new technology and average practice. Instead we rely on available, published literature that assesses the performance of these technologies and business practices.

The diversity of industries, businesses, plants, and processes implies that not all of these examples will be universally cost-effective, or even applicable. Site- or plant-specific constraints may prevent the use or economic acceptability of a technology for retrofit applications that would be readily accepted in a new plant design. In many of the most energy-intensive process industries, few green-field plants are being built in this country, further limiting some applications. While we do not consider explicitly the economics of *when* to replace old equipment, we understand that a variety of considerations enter into this business decision, including:

- How learning curves tend to continually lower the costs (including energy costs) as cumulative production experience with new technology is gained;
- Countervailing factors like "wear and tear" that tend to increase costs over time;
- How the introduction of new equipment can alter the economics of existing equipment; and
- Available design trade-offs between capital and other costs, especially energy costs.

New and replacement capacity will be put into place at many existing plants based on these and other decision variables. The opportunity for new technology to be adopted occurs at the point in time when these decisions are made. It is at this point that energy prices and capital discount rates can influence the decision to purchase new technology and thus the adoption of technologies for which examples are given below.

Many of these technology examples exhibit energy savings of more than 5-10% relative to current average practice, but the turnover rates of the capital stock in the energy- and capital-intensive industries require our projections to take this into account. In 13 years, many of these technologies (and many others not listed here) are capable of reaching higher levels of penetration, but most will not achieve 100% penetration. In addition, the technology examples often account for some fraction of the energy use in that sector. However, the examples show that there are many ways in which efficiency in industry can be increased, given the right incentives.

Brief descriptions of energy-efficient technology opportunities for the industrial sector are provided in the following sections; more details are available in the associated appendices and references.

4.4.1 Cross-Cutting Technologies

There are a variety of cross-cutting technologies that are not process- or product-specific in operation in industry. Some include lighting and heating, ventilation, and cooling technologies that are also commercial applications and are not discussed here (see Chapter 3). Others include sensors and computer control systems which have a common underlying technology, but have a variety of configurations and benefits depending on the industry. There are two major ways that all of industry can benefit from improved efficiency: cogeneration and improved motor systems.

4.4.1.1 Combined Heat and Power

Combined heat and power (CHP) is the joint production of useful steam and electricity, either for on-site use or sale back to the electric grid. There are substantial thermodynamic advantages to the joint production of heat and power that could greatly reduce generation losses from traditional power production and would reduce carbon emissions system-wide. The advantage of such an approach is that little additional fuel is required for the electricity generation over that required for simple steam production. Thus, the efficiency for use of the thermal energy available from the fuel is higher than with separate electricity generation and steam production, and the net greenhouse gas emissions can be reduced by the application of cogeneration. Based on a typical boiler configuration, the gas turbine with heat recovery steam generation is typically the most cost-effective (Boyd et al. 1996). CHP can also help reduce carbon through fuel switching to low- or no-carbon fuel. Under the BAU case, CHP power production will grow to 333 TWh by 2010. See Section 4.3.2 for an example of a CHP system that can reduce carbon emissions far more than predicted in the BAU.

4.4.1.2 Motor Systems

Energy-efficiency opportunities associated with electric motor drives derive not so much from the replacement of motors with high-efficiency motors as from energy-conscious design throughout the system employing the motor drive. Such a systems approach (see Section 4.3.2) has also resulted in significant non-energy savings when motor systems are improved.[29] The system includes power supply lines, controls, motor feed cables, the electric motor, the drive and transmission system, and the driven load. Each of these system elements may present a significant opportunity to conserve energy.

The power supply and control systems affect efficiency in three ways. First, power is consumed by resistance losses in the supply wires. Second, losses in the supply wires may contribute to voltage imbalance in the power supplied to a polyphase motor, leading to reduced efficiency and possible motor damage. Third, other system loads and certain control devices, particularly adjustable speed drives, can distort the sinusoidal AC voltage provided to the motor, resulting in efficiency and torque losses, vibration, and possible bearing damage, which is accompanied by increased friction.

Losses associated directly with the electric motor include electrical resistance losses, magnetic losses, friction and air flow losses, and stray losses associated with manufacturing quality limitations. High-efficiency motors address these losses, though efficiency improvement over standard motors may only average 5% to 7%. While an electric motor consumes less than full power when the load it serves is less than the motor rating, the efficiency of the motor declines dramatically as the load declines below 40% of rated load. Since motor over sizing is common practice, this provides a significant efficiency improvement opportunity.

Losses associated with drive systems are frictional losses in belt and gear systems. Higher losses are associated with greater speed reductions, which may improve the relative economics of adjustable speed drives (motor speed control). While drive transmission efficiency may be well over 90%, it may be below 50% as well. Thus, drive system design may offer more savings opportunity than motor replacement.

The most important savings opportunities will often lie in specification and design of the driven load. In the extreme, process changes may eliminate the need for the load entirely or equipment substitution can reduce power requirements. For instance, mechanical conveyors may be used rather than pneumatic conveyors at a substantial energy savings. More commonly, proper selection of loads such as fans, pumps, and compressors to match the intended application requirements will result in the equipment operating at higher efficiency and presenting less load to the electric motor. Then, proper matching of the remaining load to a motor, perhaps with variable speed control, will result in optimal overall system efficiency.

4.4.2 Pulp and Paper

Paper manufacturing was one of the most energy-intensive industries in the United States in 1994, using more than 18,500 Btu per dollar value of shipments. The manufacturing of paper requires that a fiber source, normally wood, be chipped, digested, bleached, and then formed as a slurry from which paper or board is made. Once formed as paper, the product must be dried. Large amounts of steam and power are used to debark and chip the wood, digest the wood, bleach the pulp, and dry the paper products. Much of this energy source (over 50%) comes from the reprocessing of lignins from the wood, bark, and unusable portions of the tree. In lumber and wood products, the fraction of biomass energy sources is nearly 70%.

In paper manufacturing, any technology that will economize the use of steam, reduce the need for heat, better utilize the biomass fuel sources available, or help to balance both steam and power needs will improve the performance of the industry. The technologies that hold promise to reduce energy and carbon emissions in the near-term continue to economize on the use of heat. Longer-term options alter the balance between steam and power. The most promising near-term options are discussed below.

Impulse Drying: Impulse drying reduces the huge energy requirements of evaporative drying by removing more water in the pressing section and reducing the amount of water which must be evaporated. The total energy savings for full implementation of this technology are estimated to be approximately 0.25 quad/yr. Without an invigorated effort, the net energy savings are estimated to be about 12 trillion Btu annually from a market penetration of only 65 drying units by 2020. Impulse drying methods allow papermaking machines to run at higher speeds, thereby increasing production rates. This drying method reduces energy use by one-third, reduces production costs by $5 per ton of paper, improves paper strength by 25%, increases productivity by as much as 80%, and reduces carbon dioxide emissions as well.

Multiport Cylinder Drying: The evaporative drying in a paper mill is accomplished by winding the continuous sheet of paper serpentine over a series of rollers. The rollers are pressurized with steam which condenses on the inside of the roller. The multiport cylinder drying concept uses an alternative method to remove the condensate from the drier, which reduces the condensate film thickness inside the drier to 25-30% of conventional technology. This improves heat transfer and increases drying.

On-Machine Sensors for Paper Properties: The development of new sensors to provide real-time feedback on whether the process and product are within specification can save the energy of reprocessing off-grade material and allow the use of greater amounts of recycled fiber. With an on-line sensor for strength properties the process variability can be reduced and greater proportions of recycled fiber utilized. A 10% reduction in refiner energy at a single mill saves more than 70 billion Btu/year. Reducing the normal off-grade production rate by 50% (from a typical 5% to 2.5%) can save an additional 118 billion Btu/year. If 300 plants adopted these sensors, the annual savings would be about 60 trillion Btu.

Biomass Gasification Cogeneration: The pulp and paper industry is about 57% energy self-sufficient, due to the use of wood residues (i.e., hog fuel and bark, pulping wastes, and cogenerated electricity). The gasification of biomass and electricity generation through a combined cycle would increase the electricity output of the paper industry, further reducing purchased electricity needs. To meet the in-plant process steam requirements, this biomass-based integrated gasification and combined cycle (BM-IGCC), would require an increased utilization of wood residues (about double) possibly from wastes in plantation forestry or other sources. If one-third of the current population of hog and bark boilers were to be replaced with BM-IGCC, many of which will be retired by 2010, then cogeneration output from the paper industry would increase by 17 billion kWh, about 27% compared to 1994 levels. This would reduce total U.S. industrial electricity purchases by 1.3% in 2010 and carbon emissions by about 1.3 million metric tons.

4.4.3 Chemicals

The chemical industry is almost too complex to characterize as a single industry. Some products – chlorine and other industrial gases – are made electrolytically or using electricity to compress and liquefy gases. Other processes, such as petrochemical processing, require high temperatures and pressures to effect the chemical combination or separation that is required. Within chemical manufacturing there are over 30 industries and more than 10,000 products. A recent study by Steinmeyer (1997) found that, in the chemicals industry, simple capital-energy tradeoffs (e.g., using larger pipes and heat exchangers) result in a 37% reduction in process energy consumption for a cost of less than 1.5% of total production costs; this study examined only energy-related costs. Another recent study by Elliot (1997) showed that productivity savings are often far larger than energy savings. For example, at the Louisiana Division of Dow Chemicals from 1982 to 1993, the average total annual savings from efficiency projects was 3.2 times the energy savings (Nelson 1993).

Reaction and separation are at the heart of most chemical engineering processes, and they typically require heat, high pressure, or both. Because of these requirements, the industry in 1994 used 5.3 quads of energy (second only to Petroleum Refining) and required nearly 16,000 Btu per dollar of product shipped. Promising technologies for the near-term are those that economize on the use of heat or cooling or bring the two in better balance. Examples are:

Pinch Analytical Techniques: The "pinch" technique was originally a method for optimizing heat recovery in thermal processes and has more recently been applied as a general optimization tool. Energy savings occur because of the heat recovery process (waste heat from one process is used to provide needed heat to another). In the classic case of heat exchanger networks, the pinch point helps to define the best match between available and needed heat, allowing the heat exchange system to be optimally sized for greatest cost-effectiveness. In early applications, energy savings averaged 30%, with capital cost savings in new plant designs, and one year paybacks in retrofits are common. Refinements to the technique have resulted in typical savings of 50% in new plants and retrofit paybacks of six months. By the mid-1980s the use of pinch analysis was widespread in the chemical industry, and its use has broadened further since then (WEC 1995).

Advanced Distillation Control Techniques: Distillation in refining and chemical industries consumes 3% of total U.S. energy use, which amounts to approximately 2.4 quads of energy annually. In addition, distillation columns usually determine the quality of final products and many times determine the maximum production rates. Distillation columns commonly use 30% to 50% more energy than is necessary to meet the product specifications. It has been estimated that an overall average 15% reduction of distillation energy consumption can be attained if better column controls are applied.

4.4.4 Petroleum Refining

The most energy-intensive processes are: distillation; catalytic hydrocracking, reforming and hydrotreating; alkylation; and hydrogen production. Efficiency improvements can be achieved in the following ways: (1) introduction of more efficient equipment; (2) reducing process activation energies (through improved catalysts); (3) improving equipment integration to recover more heat; and/or (4) adopting improved process control.

4.4.4.1 Monitoring Overall Energy Performance

Refineries could promote energy efficiency by rigorously pursuing a program to monitor equipment/process/overall refinery energy performance to identify when a system or piece of equipment begins to become inefficient so that corrective actions can be initiated.

4.4.4.2 Utility System Improvements

The principal utility systems in a refinery are the cooling, steam power, and fuel-gas systems; they are integrated with virtually every process subsystem. While their impact on the overall refinery operating profit margin is relatively small, the potential for energy savings is substantial (see appendix for details).

4.4.4.3 Process/Equipment Modifications

Major opportunities to reduce energy usage also exist through retrofitting and/or replacement of existing equipment nearing the end of its useful life. Examples of such opportunities are as follows:

Fired (Process) Heaters. Over 60% of the energy used in refineries is obtained from burning gaseous fuels in refinery heaters. For higher temperature processes such as steam reforming, the application of advanced oxy-fuel combustion systems such as Dilute Oxygen Combustion can result in net fuel savings of 25%. These gains can be enhanced further by converting natural gas to hydrogen and carbon monoxide, making use of waste heat generated by the Dilute Oxygen Combustion System.

Boilers. About 20% of all energy used by petroleum refiners is used for generation of steam. One route for improving boiler efficiency is through improved sensors and controls. For example, balancing the burners in a multi-burner boiler and reducing excess air can cut fuel use by 10 to 25%. In single-burner boilers, controlling excess air can lead to similar gains. The technology to automate excess air firing is available, but a practical system remains several years away.

4.4.4.4 Fluid Catalytic Cracking

Fluid catalytic cracking (FCC) is currently the most energy-efficient and widely used of the cracking processes. Improved computer simulations of cracking kinetics should result in an improved commercial technology by the year 2008. Introduction of improved catalysts and other process modifications would occur somewhat later. FCC improvements could eventually lead to CO_2 reductions of up to 8 MtC.

4.4.4.5 Fouling Mitigation in Heat Exchangers

Seven percent of the total energy consumed in petroleum refining is due to extra energy needed to run heat exchangers that have a fouling build-up. Research indicates that improved operations and retrofits can reduce fouling. An accelerated program of heat exchanger retrofits and better understanding of fouling conditions could reduce CO_2 emissions by 0.5 MtC by 2010.

4.4.5 Glass

The glass industry is comprised of several major product segments, each with their own processes for producing final products. The segments include container, flat glass, wool and textile fiber, specialty, lighting, and hand glass. The major common energy-intensive stage of the glass industry is the glass furnace. There are nearly 500 furnaces in over 200 plants in the glass industry (ignoring the smaller hand glass segment). While there are other stages of product finishing which also require significant amounts of energy, the examples below focus on the glass furnace as the primary area of concern for energy efficiency. Other process and product specific areas of energy efficiency are also possible.

4.4.5.1 Oxy-Fuel Process

Since 1991, the fiber, container, and specialty glass industries have accepted the oxy-fuel process as an alternative to regenerative and recuperative air-fuel furnaces. According to one source, more than 50 major furnaces (20 ton/day) have been converted to oxy-fuel combustion technology (Geiger 1996). In the oxy-fuel process, oxygen or oxygen-enriched air is used in combustion in the melting furnace. It is reported that fuel savings from oxy-fuel conversions are typically 10-15% for well designed soda-lime regenerative furnaces, and at least 30-40% for direct fired or regenerative boro-silicate or lead glasses (Ross 1996). Currently, approximately 15% of the large commercial furnaces in the U.S. have been converted to the oxy-fuel process (Ross 1996).

Oxy-fuel technology also increases furnace productivity by 25%, reduces defects, and eliminates the need for heat recovery (DOE/OIT Impacts, December 1996). There is also a waste-heat-driven thermal swing absorption (TSA) process for producing low-cost oxygen for this process. The TSA system can be used in both the glass and steel industries. This low-cost absorption system selectively absorbs oxygen from air at a cost 30% lower than the best conventional system. This new technology increases productivity dramatically, reduces fuel use by 60%, nitrogen oxides (NO_x) emissions by 50%, and particulate emissions by 30%. The system also eliminates the need for other more costly add-on NO_x and particulate control equipment to meet increasingly stringent environmental regulations for glass and metal melting. The expected energy savings are 28 trillion Btus ($70 million) annually.

4.4.5.2 Advanced Burner Technology

Adoption of newly developed burners in the oxy-fuel process further improves the energy efficiency of the process. Some recent burner designs have shown as much as a 30% decrease in fuel use, as well as improvement of product quality.

4.4.5.3 Glass Batch/Cullet Preheater Technology

The dual batch/cullet preheater uses the oxy-gas furnace's waste heat to preheat cullet and batch before feeding it to the furnace. Preheating cullet and batch reduces the amount of energy and oxygen required in the overall melting process (*GRID* 1996).

4.4.6 Aluminum

Aluminum smelting is highly capital-intensive, with capacity cost estimates ranging from $3,000 per metric ton for expansion of existing facilities to $5,000 per metric ton for new facilities (DOI 1993). Low energy costs in countries such as Brazil, Canada, and Australia have made the international aluminum industry extremely competitive, and near-term construction of smelting capacity is not expected in the United States. Investment in state-of-the-art technology has also been limited by capital constraints. A variety of technologies exist, however, that have the potential to incrementally reduce energy intensity in the aluminum industry in the time frame to 2010.

4.4.6.1 Improving Hall-Heroult Cell Efficiency

The current U.S. composite baseline energy intensity for aluminum smelting is estimated at 15.2 kWh/kg of aluminum, with the potential near-term reduction using retrofit technology estimated at 13 kWh/kg (Energetics 1997). Performance in the range of 13 to 15 kWh/kg has been achieved in domestic smelters through a variety of techniques including enhanced potline controls, better anode rod connections, improved cathode block materials, and increases in anode size resulting in lower current density (Newsted et al. 1992, Jeltsch and Franklin 1992). Additional research to design dimensionally stable cells and to optimize materials use for internal control of cells, and to use signal analysis to analyze cell voltages in potlines, are seen as areas which can improve smelting performance in the next ten years (Energetics 1997). The primary barriers to adoption of high-efficiency technologies may be economic.

4.4.6.2 Materials Recycling

Remelting aluminum scrap requires only a small fraction of the energy required to smelt aluminum from alumina. Remelting is also far less capital-intensive than smelting, which reduces barriers to modernizing. In 1995, aluminum recovered from old scrap was equivalent to about 35% of apparent consumption in the U.S. (DOI 1994). While some of the barriers to higher recycling rates are institutional (e.g., perceived value of recycling beverage containers), technological barriers also exist for some products like aluminum in cars. These include problems with scrap sorting, separation, cleaning, and pre-treatment, which inhibit the increased use of different types of scrap and also contribute to problems with metal quality. Byproduct recycling (e.g., salt cake and spent potlining) is also inhibited by a lack of knowledge of byproduct characteristics. A critical review of the U.S. recycling industry infrastructure could identify ways to enhance aluminum recycling rates (Energetics 1997). Given the magnitude of energy savings associated with recycled aluminum versus virgin aluminum, enhanced recycling may offer the greatest energy savings and greenhouse gas emissions reduction opportunities in the short term.

4.4.6.3 Improve Furnace Efficiency

Improving energy efficiency of melting and holding furnaces offers potential for energy savings in the secondary aluminum industry. Several commercially available technologies exist for reducing energy use in furnaces, including heat recuperators and regenerators and the use of oxygen-assisted combustion. Heat recuperators operate by passing the combustion products through heat exchanger tubes, thus allowing the preheating of inlet combustion air and recovery of heat that would otherwise be exhausted to the atmosphere. Heat regenerators accomplish heat recovery through a paired burner/exhaust system in which the burners alternate in the firing mode in cycles lasting about 20 seconds. Oxygen-assisted combustion uses oxygen in a dual-firing burner to increase furnace melt rates, reduce energy use, and reduce emissions. Energy savings from oxygen-assisted combustion can be substantial (Heffron et al. 1993).

4.4.7 Iron and Steel

Iron and steel industry comprises the ore-based integrated steel plants, the dominantly scrap-based "mini-mills," and specialty steel mills. Steel production via integrated plants has been decreasing, while that of the electric arc furnace (EAF) based mini-mills has been increasing. At present, the production capacity of the mini-mills is comparable to some of the smaller integrated plants. Mini-mills are more energy-efficient, since they use scrap or directly-reduced iron or hot-briquetted iron. If the mini-mill relies mainly on scrap, the range of products that can be produced is somewhat limited by scrap quality issues.

4.4.7.1 Direct Smelting / Direct Reduction

The ongoing process development activities in iron making in the U.S. and abroad clearly indicate a need to minimize coke consumption and increase the use of natural gas and/or coal as a reductant for making solid and/or liquid iron. Energy savings from such technologies arise from by-passing the coke-making stage and frequently from very high throughput. For example, Kobe Steel and Midrex Direct Reduction Corp. have developed a production approach for molten iron that reduces the process from hours to minutes (Metals Industry 1996). Because the product is in molten form, there are savings in downstream steel making operations and the material can be cooled to iron shot or ingots without reoxidation.

This technology eliminates the production of coke and reduces the need for ore preparation by integrating three steel processes into one. Coke-making and ore preparation are responsible for the largest portion of emissions in primary steelmaking. This technology reduces energy consumption by 20-30% and capital costs by 25-50% compared to conventional blast furnace technology. The first commercial applications of this technology are operating in Europe.

4.4.7.2 Scrap Preheating

Energy consumption in EAF operations can be reduced by preheating scrap to approximately 400°C with EAF offgases. Heated metal charges comprising 20-30% of inputs can result in power consumption rates of less than 300 kWh/tonne of liquid steel (Scheidig 1995). The potential energy savings is roughly 90 kWh/ton of liquid steel. For a DC Fuchs shaft furnace, compared to a conventional DC furnace, energy savings of 13.5% and reduced electrode consumption of 29% are estimated. Baghouse dust reduction is estimated at 30% (Haissig 1994). In the dual shaft furnace design, iron particles in the offgas tend to adhere to the scrap, resulting in iron recovery in the melt and leaving the offgas zinc-enriched (Burgmann and Pelts 1995). If zinc levels are enriched to above 25%, the dust may be an acceptable input to zinc refining, rather than requiring disposal as a RCRA-listed hazardous waste (Center for Metals Production 1987). Preheating also reduces furnace tap-to-tap time (normally about an hour) by 12 to 15 minutes (Scheidig 1995), resulting in increased raw steel production capacity, measured in terms of sustainable annual production.

4.4.7.3 Hot Connection

Depending on plant layout, moving forms from the continuous casting operation to the rolling operation with minimal cooling may provide energy savings. Reheat furnaces are generally employed to bring the cast forms back to rolling temperature. Adjusting plant layout to move the cast semi to the rolling operation at a temperature of 600° to 800°C can result in an energy savings of 0.4 to 0.6 GJ/tonne of semi based on the IISI reference plant defined in 1982 (Etienne and Irving 1985). A Dutch study based on a transport or connection temperature of 700°C estimated an 18% reduction in energy for reheating, for a savings of 0.3 GJ/tonne of crude steel (De Beer et al. 1994).

4.4.7.4 Near Net Shape Casting

Near net shape casting provides an example of an innovative and energy-efficient technology that has experienced rapid penetration in a capital- and energy-intensive industry. It is the direct casting of the metal into (or near to) the final shape (e.g., strips or sections), replacing the present energy- and capital-intensive processes of continuous slab casting, slab reheating, and hot rolling. Near net shape casting uses 25% less energy than the current best practice conventional technology. The first commercial application, thin slab casting, was introduced in 1989 and now accounts for one-quarter of all U.S. thin slab production capacity. Using this technique, sheet steel can be produced at a cost of $250/ton compared to conventional technology costs of $350/ton.

4.4.8 Metal Casting

Metal casting is not a single industry segment according to the SIC system, but covers a diverse group of products and metals. Products range from cast pipes, motor vehicle components, and tools. Iron, steel, aluminum, copper and zinc are all metals used by the industry. The industry is labor intensive, with many small plants; four out of five have fewer than 100 workers. Over half of the energy use is in melting metal. Technologies which improve the melting stage or reduce waste/recasting have important energy implications.

4.4.8.1 Computer-Aided Casting Design

Rapid advances in computer modeling of the casting process and in computer-aided drafting of castings have led to an increased use of computers in foundries, and hence, an increased need for integration in casting design systems. Increased integration in the casting design functions is needed to realize the full potential for improving both casting designs and production lead time. Two kinds of information are produced by the casting analysis and simulation function: (a) predicted outcome of casting the current design; and (b) the processing parameters for the casting process, if the casting design appears sound. The predictive results allow the foundry engineer to evaluate the filling of the mold cavity, the potential for defects such as porosity in the casting to occur, the sequence of solidification, and the time for complete solidification. With computer modeling, an average of 25% improvement was found in casting yield (Lensen 1996, Lensen et al. 1995), which would comparably reduce energy use for metal remelting.

4.4.8.2 Optimized Coreless Induction Melting

Most foundries can dramatically reduce a major portion of their energy through optimization of their induction melting equipment. It has been estimated that foundries are only operating their induction furnaces at 50-80% of their optimal efficiency (Horwath et al. 1996). A foundry melting 1000 tons/month could reduce its monthly melting costs by $5/ton by installing sensors and computer optimization of its melting practice. Four major variables are important in determining the power required for melting: (1) charge makeup, (2) furnace cover, (3) power application, and (4) furnace condition. In some cases, optimal material use resulted in higher energy use (22% more). Use of a furnace cover reduced energy consumption by 12%. Furnace condition (i.e., hot, medium, or cold) interacts with the charge to significantly affect energy consumption. Maintaining the furnace in hot condition resulted in 15.4% less energy consumption for melting the charge (Horwath et al. 1996).

4.5 THE LONGER TERM: FUTURE TECHNOLOGIES AND R&D POTENTIAL

The technologies cited above are currently available, or soon will be, because of past R&D. For future technologies to contribute to increased energy and emissions reductions presumes a continued stream of R&D activities into the future. Recent efforts by the Department of Energy are directed at ensuring that steady stream of R&D by partnering with industry.

The Office of Industrial Technologies, in an effort to garner support and make their research and development activities more in line with the needs of industry, has initiated a joint government-industry planning process called the "Industries of the Future." The vision of the way that future industry will function and the technologies that the industry will use shapes, in part, the organization and implementation of government R&D efforts. It is this process that may lead to an invigorated effort to develop future technologies that will improve energy efficiency and reduce carbon emissions.

In this section we discuss the potential for additional decreases in energy intensity in the future as a result of the continuation of future R&D efforts. Here we draw heavily on the vision documents that have been published or are being prepared by the energy-intensive industries under the OIT's Industries of the Future process. We discuss general areas of potential advancement or provide specific examples of some of the technologies or technology areas that show particular promise for reducing energy consumption and concomitant greenhouse gas emissions.

4.5.1 Pulp and Paper

The Vision process for the Forest Products Industry of the Future was developed by the industry in collaboration with the Department of Energy's Office of Industrial Technologies, and is called "Agenda 2020 – A Technology Vision and Research Agenda for America's Forest, Wood, and Paper Industry." Two of the major concerns of this document are Environmental Performance and Energy Performance. One way these objectives might be met is through the use of polyoxometalate bleaching.

4.5.1.1 Polyoxometalate Bleaching

Traditionally, the last remnants of lignin from the pulp have been removed with a chlorine bleaching process. However, the environmental impacts of chlorine have lead to significant efforts to find alternative methods to produce a desirable soft white fiber. Among these have been ozone bleaching and peroxide bleaching. Unfortunately, nothing has come to market which is as effective and selective as chlorine or chlorine dioxide. Polyoxometalates may be just such a new process. They are highly selective and can be regenerated within the process. In addition to desirable performance characteristics, the polyoxometalate system is consistent with the goals of increasing recycling of process water and reducing the effluent load from pulp mills. Compared to chlorine based systems, the new process promises to reduce electrical energy consumption of pulp bleaching by 50%.

4.5.2 Chemicals

4.5.2.1 Biological/Chemical Caprolactam Process

Nylon-6 is currently produced from caprolactam. The chemical synthesis of caprolactam from cumene is a complex, multi-step process that is energy-intensive and generates considerable waste. Nylon-6 could also be produced from caprolactone. However, the current market price for caprolactone makes this route uneconomical.

A laboratory-demonstrated biological process has been developed that would provide a one-step, cost-effective production process for caprolactam manufacture that requires 50% less energy than the current process, costs half as much (considering both capital and energy costs), and produces almost no waste byproducts. Research on this process has established the technical feasibility of the biomanufacturing process for converting inexpensive cyclohexane into caprolactone. Under this project, the feasibility of the laboratory-demonstrated biomanufacturing process was established, and the process is now available to be optimized for possible scale-up to pilot plant scale. It is estimated that, by the year 2020, this technology can provide annual energy savings of 12 trillion Btu (DOE 1997). While this is a modest total savings (the chemical industry used over five quads in 1991), this is just one of tens of thousands of chemical processes.

4.5.2.2 Flexible Chemical Processing of Polymeric Materials

Waste textiles and recycled waste materials from automobiles, appliances, and furniture contain polymers (such as nylon-6, nylon-66, PET, and polyurethanes) that can be converted into valuable chemical feed stocks. However, processes that can only convert a single type of recycled material can face high costs for material collection and for transportation of the resulting feed stocks. Because these costs are the major contributors to process costs, processes are needed that can convert a variety of recycled materials.

Research in this area is working toward developing a thermochemical process that can convert a wide variety of recycled materials into valuable chemicals. A two-stage process is envisioned: the first will use selective catalytic pyrolysis to recover chemicals such as caprolactam, hexamethylendiamine, and dimethyl-terephathalate; the second will convert the unreacted organic material into synthesis gas, which can be converted to a variety of chemicals of use to the chemical industry.

Because the process can address a wide variety of recycled materials, large regional recycling plants can be developed, lowering material collection and transportation costs, and thereby increasing the viability of recycling many materials. It is estimated that, by the year 2020, the use of this technology will save 265 trillion Btu annually (DOE 1997).

4.5.2.3 Genetic Engineering

Many chemicals firms are investing heavily in genetic engineering and, over the next decade, many expect to commercialize products. Low-carbon biotechnologies include engineered plant systems to allow crops to fix their own nitrogen from the air (thus avoiding N_20 emissions associated with fertilizer manufacture); agricultural "petroleum plants" that grow feed stocks for the chemicals industry; and intermediate products such as polymers.

4.5.3 Petroleum Refining

The National Petroleum Council issued a report in 1995, "Research, Development, and Demonstration Needs on the Oil and Gas Industry", which identifies the future of the industry in 2020. It stresses, among other things, the need for flexibility in processes as well as new chemistries and materials. Changing input feed stocks and environmental requirements will tend to push the industry toward higher energy use in 2020, without developments such as new catalysts or other process changes that are on the horizon.

4.5.3.1 Development of Improved Catalysts

The purpose of a catalyst is not to lower the energy needs of a reaction (which are governed by thermodynamics) but to lower the energy required to activate a process and thereby increase the kinetics and/or product selectivity. If it accomplishes either or both of these tasks, the energy demands on a given process should decrease either due to lower heat demand (lower energy of activation) or from greater throughput. Most of the energy use in a refinery that could benefit from improvements in catalyst technology is consumed in one of three major process areas: (1) hydroprocessing, (2) catalytic cracking, and (3) alkylation.

In hydroprocessing, much energy is utilized in heating up heavy oils and resids to temperatures at which the catalyst activity is high enough. Additional energy is expended in the compression of hydrogen to pressures up to 2000 psi. Improved catalysts (capable of functioning at lower temperatures and pressures) could reduce the energy used by decreasing the reaction temperature of this process.

Energy usage could be improved for catalytic cracking in terms of product selectivity. Cracking catalysts are extremely efficient at converting "good" gas oils to gasoline and distillate. However, when significant fractions of resid and the metals that accompany these resids are used as fluid catalytic cracking (FCC) feeds, the selectivity (in terms of gasoline yield) drops precipitously. This gasoline loss comes at the expense of increased coke and dry gas production, which in turn requires catalyst coolers in order to keep the temperature of the catalyst bed down (required by increased coke burn) and higher compressor capacity to handle the increased dry gas yield. If catalysts were designed to handle higher amounts of heavy oils without the detrimental effects outlined above, then more resid could be handled in the highly efficient FCC with resulting decreased utilization of the less efficient hydrotreaters.

The largest energy demand in the alkylation units are in the refrigeration units used to keep the hydrofluoric acid temperature down. Here the need is for a catalyst which will operate at temperature above ambient. Many solid alkylation catalysts which are in pre-commercial testing and evaluation function at temperatures around 150°C. Many of the streams requiring alkylation are at or near this temperature when they exit their respective processing units. Such heat is normally considered waste heat and thus could easily be utilized for the alkylation process. Therefore, even though the reaction temperature would go up, the energy demand would decrease.

4.5.4 Glass

The glass industry vision of itself in 2020 is defined in "Glass: A Clear Vision for a Bright Future". This vision document includes, as one of many goals, reducing process energy use from present levels to 50% toward the theoretical limit of 2.2 million Btu required to melt a ton of glass. On April 29, 1996 a compact between the DOE and the major glass producing companies was signed to enable collaboration in such areas as waste reduction, energy efficiency, and quality control. The technology road map is currently under preparation. The technologies below are just a few examples of areas of glass industry technology development.

4.5.4.1 Optimizing Electric Boost to Reduce Total Energy Consumption

High energy efficiency, through conversion of electric energy into useful heat, and low volatilization are the primary advantages of electric melting. Current operating practice has shown that effective use of electricity near the back end of the furnace, where the batch is added, can reduce fossil fuel needs. Research needs for optimizing electric boost include, but are not limited to, investigating new electrode and electric arc melting processes, modeling of the current technology to fine-tune operation conditions, such as energy inputs and locations of the electrodes, and improving the electrode control system (Glass Industry Working Group).

4.5.4.2 Recovering and Reusing Waste Heat from Oxy-Fired Furnaces

Recovery and reuse of waste heat from the oxy-fuel process will further increase energy efficiency of the process. Preheating the batch and cullet, described above, is one method to recover heat from the flue gas. Other options, such as regenerative oxygen heat recovery (Browning and Nabors 1996) and a "synthetic air" concept (Argent 1997), have been proposed and need to be tested and evaluated. A Thermal Swing Adsorption (TSA) oxygen production process has been demonstrated in the laboratory with enrichments of up to 89%. The process is based on synthetic chemicals that can reversibly bind oxygen at low temperatures and release it at elevated temperatures. The operation is in a temperature range of 70° to 220°F, so low grade waste heat can be used to drive the process, and the external energy required for produce oxygen can be reduced.

4.5.5 Iron and Steel

"Steel – A National Resource for the Future" broadly defines four areas of R&D to shape the industry in 2020. These include production efficiency (which encompasses energy efficiency), recycling, environmental engineering, and product development. The goal of increasing steel production to over 70% of recovered scrap would have major implications for energy use. DOE and the two major steel industry trade groups have signed a R&D collaborative compact to work together on the first three of the four research areas. Below, we discuss some of the process areas within which energy and other savings are likely to be achieved from technical breakthroughs.

Activity will be largely dictated by the viability of different iron making processes that are under development. R&D effort should focus on developing a process scheme that incorporates both iron making and steel making into one system with thin strip casting as a final product. The effort should incorporate a coal-based reductant process which can be coupled with steel making operations and simultaneously produce power in a combined cycle that includes both gas and steam turbines.

Steel making processes currently utilize computer technology, primarily to implement prespecified procedures in a timely manner. There is very little feedback in these systems to either enhance process efficiency or improve the product quality. Key process parameters should be identified so that interactive logic and high-speed computer systems can be used to control/modify/maintain these process parameters to obtain a quality product. Such an intelligent-processing approach is essential for the production of so called "cleaner steel" with low residual elements.

The development of sensors for all aspects of process control and for enabling process changes with a feedback system is essential for improving process efficiency and optimizing different stages of the melting, casting, thermomechanical processing, and final heat treatment. Applications of novel ideas and approaches need to be explored and transfer of technologies available from defense and chemical processing industries may be a fruitful approach.

4.5.6 Metal Casting

A diverse group of CEOs and presidents from the foundry, die casting, and foundry supply companies co-authored "Beyond 2000: A Vision for the American Metal Casting Industry." This vision of the industry identifies six critical areas: production efficiency; recycling; pollution prevention; application development; process controls; and new technology development. The specific goals include increasing productivity by 15% and reducing energy consumption by 3-5% by 2010. The Cast Metals Coalition is preparing a R&D strategy to achieve these and other goals identified in the industry vision. Some examples of technology areas are given below.

Electromagnetic Casting: An electromagnetic field in a casting is used to induce eddy currents in the liquid metal that, together with the field, stir and contain the liquid metal in the casting. Two examples are discussed below:

EM Stirring: In continuous casting, the solidification process can be improved by EM stirring, producing better metallurgical results, improved internal quality of the casting, and even reduced meniscus instability and surface defects (Beitelman and Mulcahy 1994, Chang et al. 1995). The benefit from EM stirring takes the form of reduced wastage per cast. As a minimum, we expect that the present average yield of 55% for the industry can be increased to 65%, a savings of 130,000 tons per year, with an associated energy savings of 25 trillion Btu per year (American Foundrymen's Society 1995).

EM Confinement: In the presently dominant sheet-forming process, thick steel slabs are cast and then hot-rolled. Twin-roll casting with EM confinement has the potential to cast thin sheets by eliminating the hot-rolling stage, giving the sheet product an enormous economic advantage over products made by competing methods (Saucedo and Blazek 1994, Blazek et al. 1994) and completely by-passing an energy-intensive stage of production.

4.6 CONCLUSIONS

This chapter presents an approach to assessing the potential for efficiency to reduce energy use in the most diverse sector of the economy, the industrial sector; this approach represents a compromise between the desire for technology detail and the need to evaluate sector-wide energy use. The approach uses two publicly available models, Argonne's Long-term Industrial Energy Forecasting (LIEF) model and the Energy Information Administration's industrial module from the National Energy Modeling System (NEMS), to simulate a plausibly optimistic set of scenarios for additional energy savings, relative to an established base case (AEO97). The models are used to project what energy savings could arise from an 'invigorated effort' to put currently available or near commercial technologies into practice in industry. This invigorated effort is loosely characterized by either a combination of new policy initiatives or a more serious consideration of efficiency as a strategic concern of industrial decision makers.

Two efficiency cases are presented in order to project overall reductions in energy use by 2010. A reduction of 5-10% is projected to be technically feasible, given adequate policies or other incentives to expand the adoption of cost-effective measures. This is about 2.5 quads in the high case. The LIEF model projects that these reductions could arise from cost-effective investments defined by a capital recovery factor of 15% (about a seven year pay-back). The LIEF model does not assume that in every case all energy-efficiency investments are made, but an increased penetration rate of efficiency investment is assumed relative to the base case as a result of this 'invigorated effort'. For many of the energy-intensive industrial sectors, these projected energy savings are consistent with roughly doubling the current rates of capital stock replacement or doubling the rate of energy technology efficiency improvement that is currently represented in the NEMS model.

Since the models used to conduct the scenario analysis do not have a detailed, technology-specific representation of each major industrial sector, the chapter also provides illustrative examples of technologies for most of the energy-intensive industries. These are examples of technologies that have the potential to reduce energy use relative to current practices if widely adopted. These technology examples exhibit substantial energy savings relative to current industry practice, so they reinforce the fact that the model results are feasible. But one cannot expect these technologies to be adopted widely unless there is some invigorated effort to encourage their adoption. The slow turnover of the capital stock in the energy and capital intensive industries is one reason that this invigorated effort would be needed. Under conservative projections, in the near-term, many of these technologies (and the many others not listed here) are capable of reaching high levels of penetration but most will not achieve 100% penetration. However, the examples show that there are many ways in which efficiency in industry can be increased, given the right incentives; the examples help establish the technical plausibility of the projections.

The efficiency case projections also show that, on a percentage basis, there are more savings in 'light' non-energy-intensive industry vs. the 'heavy', energy-intensive sectors. This result arises from the LIEF model scenarios but, due to the structure of the model, does not have an analog in NEMS. Because the share of total production costs attributable to energy use in the non-energy-intensive sectors is very low (the manufacturing average is about 3% and most light industry is less), it is not surprising that the range of energy performance is quite broad. Energy-efficient technologies, in the form of motor systems as well as lighting and HVAC options (similar to those discussed in the commercial section of Chapter 3), represent cost-effective investment opportunities in light manufacturing. However, there may not have been a managerial or technical focus on energy efficiency in those industries. An 'invigorated effort' could provide this focus. On the other hand, to reduce energy use in 'heavy' industry, where considerable attention to efficiency has already been paid, low capital turnover rates and difficulty in financing medium to large investments may be the major impediments to accelerated improvements in energy utilization. This 'invigorated effort' in these sectors might require tax incentives, alternative financing arrangements, new developments that lower first cost, or demonstration projects that lower perceived risk. The diversity among these broad categories of industry implies that the mix of policies required to achieve the high-efficiency case may differ for the various types of industries, based on their current business and technical practices as well as current domestic and international market conditions.

For all of the industries discussed above, further progress in energy efficiency beyond 2010 requires further developments in technology. These developments may be *incremental* improvements (e.g., sensors, controls, and system/process modeling) or may be *fundamental* breakthroughs (e.g., catalysts, direct smelting, or bioprocessing). Incremental improvements need not be associated with 'small' efficiency changes. The ability to sense and adjust a process to achieve optimal operating conditions can have large effects on productivity and energy consumption. However, the search for totally new methods to produce a product with fundamental breakthroughs in chemistry, metallurgy, or biology offers another route to enhance productivity and lower energy use. These two avenues of R&D to create the manufacturing sector of 2020 are both being sought by private and private/public partnerships.

Table 4.15 summarizes the technology examples presented above. A rough categorization of incremental (I) and fundamental (F) has been made. Many of the underlying concepts in the examples apply to other sectors, while others are very process specific. This identification is made as well. In should be noted that the year 2010 designates current (on very near commercial) technologies, while the year 2020 designates technologies that will require further R&D, with no prediction of a commercialization date.

The range and types of technological solutions in industrial applications is quite large. Since energy represents a cost, and energy efficiency a potential source of profit, these technical solutions can fit within the economic goals of business. With the right incentives, higher energy efficiency of the magnitude projected here in the industrial sector is an achievable goal.

Table 4.15 Summary of Technology Examples

Example Taken From	Technology Example	Year	Type of change: incremental or fundamental	Concept applicable to other sectors	Saves fossil or electric energy
Aluminum	Improve Furnace Efficiency	2010	I	Y	EF
Aluminum	Materials Recycling	2010	I	Y	E
Aluminum	Improving Hall-Heroult Cell Efficiency	2010	I	N	E
Aluminum	Wettable Cathodes	2010*	I	N	E
Aluminum	Inert Anodes	2010*	I	N	E
Chemicals	Pinch Analytical Techniques	2010	I	Y	F
Chemicals	Advanced Distillation Control Techniques	2010	I	N	F
Chemicals	Flexible Chemical Processing Of Polymers	2020	F	N	F
Chemicals	Biological/Chemical Caprolactam Process	2020	F	N	F
Cross-cutting	Combined Heat and Power	2010	I	Y	EF
Cross-cutting	Motor Systems	2010	I	Y	E
Glass	Glass Batch/Cullet Preheater Technology	2010	I	Y	F
Glass	Advanced Burner Technology	2010	I	Y	F
Glass	Oxy-Fuel Process	2010	I	N	F
Glass	Producing Oxygen More Efficiently	2020	I	Y	E
Glass	Recovering Waste Heat	2020	I	Y	F
Glass	Maximize Combustion Efficiency	2020	I	Y	F
Glass	Optimizing Electric Boost	2020	I	N	F
Iron and Steel	Process Controls	2010	I	Y	EF
Iron and Steel	Hot Connection	2010	I	Y	F
Iron and Steel	Scrap Preheating	2010	I	Y	EF
Iron and Steel	Use Of DC, Rather Than AC, EAFs	2010	I	N	E
Iron and Steel	Coal Or Natural Gas Injection	2010	F	N	F
Iron and Steel	Direct Smelting / Reduction	2010	F	N	F
Iron and Steel	Process Controls And Sensors	2020	I	Y	EF
Iron and Steel	Direct Smelting & Thin Strip Casting	2020	F	N	EF
Metal Casting	Computer-Aided Casting Design	2010	I	Y	EF
Metal Casting	Optimized Coreless Induction Melting	2010	I	N	E
Metal Casting	Electromagnetic Stirring	2020	I	N	EF
Metal Casting	Electromagnetic Casting	2020	F	N	EF
Petroleum Refining	Utility System Improvements	2010	I	Y	F
Petroleum Refining	Process/Equipment Modifications	2010	I	N	F
Petroleum Refining	Development Of Improved Catalysts	2020	F	Y	F
Pulp and Paper	On-Machine Sensors For Paper Properties	2010	I	Y	F
Pulp and Paper	Multiport Cylinder Drying	2010	I	N	F
Pulp and Paper	Impulse Drying	2010	I	N	F
Pulp and Paper	Biomass Gasification	2010*	I	Y	EF
Pulp and Paper	Black Liquor Gasification	2010*	I	N	EF
Pulp and Paper	Sulfur Free Pulping	2020	F	N	EF
Pulp and Paper	Polyoxometalate Bleaching	2020	F	N	EF

* Based on the accelerated deployment described in Section 4.3.

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ENDNOTES

[1] Because they become very important in a low-carbon scenario, we have made an exception to this approach in the case of low-carbon technologies which are examined from the bottom-up. Unlike energy-efficiency technologies, there is no established modeling procedure or analysis method for assessing the penetration of low-carbon (especially low process carbon) technologies. Thus, we simply provide case studies and take their results as a lower bound on the potential.

[2] Differences in the industry subsector detail prevented us from doing a precise calibration of the two models. It is not clear that such a calibration would substantially improve our analysis for these purposes.

[3] Technologies that supplement the existing process (e.g., process controls) might penetrate rapidly, but most that are replacements for existing process will more likely follow the 'normal' turnover patterns. Technologies achieving rapid penetration include sensors and process control software and technologies that can save significant amounts of energy.

[4] The forest products industry includes pulp and paper, as well as lumber and wood products. This report focuses on the relatively more energy-intensive pulp and paper segment of the forest product industry.

[5] In particular, we do not change the underlying forecast for activity in the refining sector.

[6] The HE/LC case also includes low-carbon technologies described in Section 4.4. These low-carbon technologies are not explicitly captured in the computer model runs.

[7] Not all energy-intensive industries are "heavy." The metal casting industry, for example, consists of many small shops owned by small businesses. It is important to distinguish OIT's Industries of the Future and the "heavy industry" of Table 4.1. These "heavy" industries include non-vision industries such as food (SIC 20), non-refining petroleum (SIC 295, 299), stone, clay and cement (SIC 324-329), non-aluminum non-ferrous (SIC 3331, 3339, 3351, 3356, 3357, 3364, 3366, 3369). Conversely, the vision industries include wood and lumber (SIC 24), miscellaneous paper (SIC 265, 267), and miscellaneous chemicals (SIC 283, 285, 2879, 289), which are not included in the "heavy" industry of Table 4.1.

[8] These numbers are calculated from the numbers in Appendix A for Figure 16 in DOE (1995).

[9] Note that, in Figure 4.3, ATS in simple cycle power-only mode has a higher heat rate than the most efficient combined cycle turbine. However, even the power-only ATS emits far less CO_2 than the existing sources of power to the grid. In our calculation of the carbon reductions for ATS in power-only applications, we make the conservative assumption that the ATS has about the same emissions as new power plants. The carbon savings in this market come only from avoided T&D.

[10] As an average of 3 to 18 MW units (9 to 80 MW in multiple units), ATS are 43% efficient in simple cycle and can be 80 – 85% efficient (combined thermal and electric efficiency) when used for cogeneration (Hoffman, 1997).

[11] Constraints to growth of cogeneration have derived in part from the traditional requirement that steam and electricity loads be matched to maintain efficient and cost-effective operation of the cogenerator. The new ATS overcomes this problem by running efficiently at a wide range of electricity to thermal ratios. Cogeneration has also been constrained by environmental permitting, utility regulation, and utility competition. Together these factors explain why very efficient CHP technology still comprises a relatively small fraction of electricity and steam generation. When policies to promote CHP are instituted, however, this fraction can grow dramatically (Major 1995). Finland, Denmark, and the Netherlands have each achieved a contribution of about 30% of electricity production based on CHP.

[12] In the recuperator configuration hot exhaust gas from the turbine is used to preheat the air leaving

the compressor prior to combustion, thereby reducing the amount of fuel required to reach the design turbine inlet temperature.

[13] See Appendix D-3 for details.

[14] Such reform would include standardized permits to reduce costs for small sites and a life cycle approach that takes into account power plant emissions and T&D for on site power permits.

[15] Current regulations, and some proposed utility deregulation legislation, include barriers to small on-site CHP. Both scenarios assume policies that elicit the cooperation of utilities in the increase in on-site generation. One scenario that could be imagined is that the utilities themselves finance and service these industrial ATS's for CHP and power generation.

[16] Carbon reductions from fuel switching were not included – a conservative assumption discussed in Apendix D-3.

[14]The calculations performed for both scenarios were reviewed by the American Forest and Paper Association and industry representatives (David Cooper and Delmar R. Raymond).

[18] The makeup of residual biomass and residue generation rates in various forest product and paper industries are described in Appendix D-5.

[19] Three large plants in the U.S. manufacture adipic acid and they are working with the EPA to reduce emissions (Boyd 1997). However, emissions from this process have increased by 9.9% since 1990.

[20] Many of the U.S. aluminum smelters are located in regions of the country with large hydropower resources, notably the Pacific Northwest (served by the Bonneville Power Administration), the Southeast (served by the Tennessee Valley Authority), and Northern New York. Under both scenarios, the aluminum smelters that would likely be converted first would be those in regions such as the Ohio River Valley that are dominated by coal-powered plants.

[21] 0.2 MtC = [(5 plants) * (190,000 tonnes of AL/plant)* (13,200 kWh/tonne of AL) * (89 gr of carbon per kWh) * 0.17]/1,000,000 grams/tonne.

[22] The carbon savings from the aluminum industry efficiency improvements that are already included in Section 4.2.2 must be subtracted in order to identify the increment that can be added by this analysis of alternative aluminum production cells. We calculate this as follows. Table 4.2 estimates that the aluminum industry as a whole will be 2% more efficient in its use of electricity in 2010 under the efficiency scenario, compared to the business-as-usual case. Under the assumption here that 5 of 22 smelters (23%) will be retrofitted with wettable cathodes that offer a 17% improvement in electricity efficiency, the nation's aluminum smelters as a whole would be 3.9% more efficient (3.9% = 0.23 * 17%). This represents a 1.9% efficiency improvement (or 0.09 MtC of emissions reductions) over the 2% that is assumed in the efficiency case in Section 4.2.2.

[23] 0.48 = (5 of 22 plants) * (50%) * 4.2 MtC.

[24] 1.0 MtC = [(10 plants) * (190,000 tonnes of AL/plant)* (13,200 kWh/tonne of AL) * (160 gr of carbon per kWh) * 0.25]/1,000,000 grams/tonne.

[25] The carbon savings from the aluminum industry efficiency improvements that are already included in Section 4.2.2 must be subtracted in order to identify the increment that can be added by this analysis of alternative production cells. We calculate this as follows. Table 4.2 estimates that the aluminum industry as a whole will be 3.8% more efficient in its use of electricity in 2010 under the high-efficiency/low-carbon scenario, compared to the business-as-usual case. Under the assumption here that 10 of 22 smelters (45%) will be retrofitted with inert anodes that offer a 25% improvement in electricity efficiency, the nation's aluminum smelters as a whole would be 11.4% more efficient (11.4% = 0.45 * 25%). This represents a 7.6% efficiency improvement (or 0.67 MtC of emissions reductions) over the 3.8% efficiency improvement that is assumed in Section 4.2.2.

[26] 0.6 MtC = (10 plants) * (190,000 tonnes of Al/plant) * (0.33 tonnes of C/tonne of AL).

[27] 1.91 MtC = (10 of 22 plants) * (100%) * 4.2 MtC.

[28] Note that almost none of the carbon savings due to Section 4.2.2's high-efficiency/low-carbon (HE/LC) case should be subtracted from this amount. The clinker replacement is not an efficiency increase, but a demand reduction. Thus, the drop in carbon emissions is nearly additive. We subtracted a very small amount because of the 8.1% reduction in cement industry energy use under the HE/LC scenario. The carbon savings due to a 5-20% reduction in demand is 2-4 MtC depending on the kiln technology. The amount we subtracted is about 5% of the total (0.06-0.08 MtC). If we assume that the penetration by 2010 is limited to the European owned firms (roughly half), then the carbon reduction is 1-2 MtC. Note that the HE/LC energy efficiency savings of Section 4.2.2 are equivalent to a carbon emissions reduction of just over 1 MtC depending on cement kiln technology.

[29] The Greenville Tube Company (GT) realized non-energy benefits ten times greater than the energy benefits when the company upgraded its motors. GT is a manufacturer of high-precision, small-diameter, stainless steel tubing. GT replaced an old motor and inefficient eddy current clutch drive with an energy-efficient motor with vector control. This new motor required fewer runs and produced far less scrap than the old system. The motor reduced annual energy consumption by 37% and resulted in savings of more than $77,000 annually from increased productivity, reduced scrap generation, and reduced energy costs.

Chapter 5

TRANSPORTATION SECTOR

5.1 INTRODUCTION

The trend of more than a decade of continuous energy-efficiency improvements in transportation, marked by a sharp decoupling of energy consumption and economic growth, appears to have come to an end. The transportation sector's energy use now appears to be growing at nearly the same rate as the gross domestic product (GDP).

From 1949 until 1973, energy use in the U.S. transportation sector grew at an average annual rate of 3.6% per year (EIA, 1996a, Table 2.1). In the years following the oil crisis of 1973-74 until the oil price collapse of 1986, that rate fell to only 0.6% per year.[1] This sharp decrease in growth was caused by a combination of market and non-market factors – sharply rising oil prices and, perhaps more important, strong expectations that prices would continue to escalate for the foreseeable future; threats of gasoline rationing and actual (though largely government-caused) local gasoline shortages; successes in government-sponsored R&D, especially in aeronautics; and new regulations, particularly the Corporate Average Fuel Economy (CAFE) standards for automobiles and light trucks. Some manifestations of the decrease in the growth of energy use during this period were:

- Between 1973 and 1988, new passenger cars increased their fuel economy from about 14 MPG to 28.6 MPG (EPA rated) (Heavenrich and Hellman, 1996, Table 1), a rate of 5% per year.
- During 1970-1987, commercial aviation decreased in energy intensity from 10,351 Btu per passenger-mile to 4,753 Btu/pm (Davis and McFarlin, 1996, Table 2.16) again at an average rate of 5% per year.
- During 1970-1994, the energy intensity of rail freight decreased from 691 Btu/ton-mile to 388 Btu/ton-mile, or 44% (Davis and McFarlin, 1996, Table 2.17), a rate of 2.4% per year.

Although changes in travel behavior, choice of vehicle size, changes in vehicle occupancy rates and other non-technological factors have a role in the rate of growth in transportation energy use, improved technological efficiency has been the most critical factor in energy trends. For example, had energy intensities not changed since 1972, commercial airlines would be using over twice the energy they use today (assuming today's number of passenger-miles of travel), and three quarters of the savings are due to technological improvements in aircraft (Davis and McFarlin, 1996, Table 2.21). Similarly, examination of the causes of substantial fuel economy gains by automobiles during the 1970s and 1980s show that the majority of the gains were achieved by improving technical efficiency, not by consumers moving to small cars. Between 1978 and 1984, only 7.8% of the period's MPG gain was achieved by shifts to smaller cars (Westbrook and Patterson, 1985). Between 1976 and 1989, the combination of weight reduction, improved transmissions, tires, and aerodynamics, widespread use of fuel injection, various engine improvements, improved lubricants, and wider use of front wheel drive accounted for about 70% of the total 8.4 MPG improvement during the period (Westbrook, 1989). In fact, the technology of automobiles has improved so much over the past few decades that if the 4,000 pound plus, 15.8 MPG automobile of 1975 were to be built with today's technology but *without any change in weight or horsepower*, it would get 26.4 MPG (Greene and Fan, 1994)! And although 85% of the improvement in rail freight energy efficiency came from increased loadings per car, much of the 85% resulted from improved communications and computing capability (other factors included changing composition of freight during this period and other operational improvements), and improved vehicle technology accounted for the remaining 15% (Greene, 1996).

Over the past ten years (1986-1996), the rate of growth of transportation energy use has averaged 1.6% per year, but in the past three years it accelerated to 2.2% per year, just below the rate of growth of GDP. Transportation energy efficiency, which improved significantly during the decade of the 1980s, appears to be stagnant (U.S. DOT/BTS, 1996, p. 87). The average fuel economy of new passenger cars has not improved significantly over the past decade. The average fuel economy of light-duty vehicles, new cars, and light trucks combined has not changed significantly since 1982 (Heavenrich and Hellman, 1996, Table 1) and, as a consequence, the average on-road fuel economy of the entire on-road light-duty vehicle fleet was only 1% higher in 1995 (the most recent year for which data are available) than in 1991 (U.S. DOT/FHWA, 1996, Table VM-1). Gasoline prices are now at pre-1973 levels and fuel economy standards have not been raised over 1985 levels. There are exceptions, however: commercial air travel and rail freight continue to make meaningful efficiency gains (U.S. DOT/BTS, 1996, p. 101). Overall, the transportation sector appears to have entered a period of growth in activity only slightly slower than that of GDP with only modest gains or no improvement in energy efficiency.

Despite these recent trends, the 1997 Annual Energy Outlook (AEO97) reference case forecast to 2015, which serves as the backdrop for this analysis, foresees very slow growth in transportation energy use (1.4%/yr.) accompanied by virtually no change in the prices of transportation fuels (0.2%/yr.). A modest rate of growth in vehicle travel (1.4%/yr.) together with MPG gains of 5.1 MPG for new passenger cars and 3.7 MPG for new light trucks over 1995 levels, combine to hold the growth of light-duty vehicle energy use to 1% per year through 2015. Every year since at least 1989, the AEO (among others) has forecasted continued light-duty vehicle fuel economy gains yet the actual fuel economy of light-duty vehicles as a whole has not improved. In some cases, energy prices have turned out to be lower and in other cases higher than expected. Apparently, technology that could have been used to improve fuel economy is either not being implemented, or is being used to provide some other feature that consumers value, such as performance. We expand on this point below in explaining why, in our "business-as-usual" (BAU) case, we forecast no improvement in light-duty vehicle fuel economy. We believe that, given low energy prices, plentiful oil supplies, no market disruptions, and no new energy policy initiatives, it is optimistic to expect continued energy-efficiency improvement and slow growth of energy use.

Current policy initiatives and activities to increase future transportation energy efficiency are relatively modest. Except for light-duty highway vehicles, the federal government does not regulate transportation fuel efficiency. The National Highway Traffic Safety Administration has the power to raise CAFE standards for autos and light trucks, but there seems little chance that it will do so at the present time. The Energy Policy Act contains provisions to move alternative fuel vehicles into the fleet (fleet vehicle requirements and altfuel tax credits), but these provisions are limited, and congressional support for coercive action is nonexistent. On the other hand, there are important R&D initiatives that could play a role in improving transportation fuel efficiency, particularly the long-standing NASA and Defense Department programs in aeronautic design and the Partnership for a New Generation of Vehicles (PNGV), a joint government/industry research effort aimed primarily at developing vehicles with up to three times current fuel economy levels.

The newest of federal initiatives aimed at improving transportation fuel efficiency, PNGV has reorganized and redirected the federal government's R&D effort in advanced automotive technologies towards the ambitious goal of tripling automotive fuel economy and reducing pollutant emissions while at the same time preserving consumer amenities and holding down costs. Current PNGV spending is on the order of $250 million dollars (the exact amount is subject to debate because of definitional problems of which efforts are actually dedicated to PNGV goals) (U.S. Congress, OTA, 1995), with the largest government share coming from DOE's Electric and Hybrid Vehicle Program. Current PNGV thinking seems aimed at an advanced hybrid-electric vehicle, with research efforts aimed particularly at advanced materials, high-power energy storage devices, fuel cells and improved engines, lean NO_X catalysts (to allow necessary emission control for lean-burn engines including diesels and direct injection stratified charge engines), and improved electric drives, including power electronics.

In this chapter, the potential for these and other energy-efficient and low-CO_2 technologies to cost-effectively reduce transport sector greenhouse gas emissions is examined. Three transportation sector scenarios were developed using the Energy Information Administration's (EIA) National Energy Modeling System (NEMS) model, AEO97 version (see Overview of Methodology box), with reference case assumptions about macroeconomics and energy prices (Decision Analysis Corp., 1996; EIA, 1994). These are labeled the (1) "business-as-usual" (BAU), (2) "efficiency" (EFF), and (3) "high-efficiency/low-carbon" (HE/LC) cases. Our business-as-usual case differs from the AEO97 reference case only in that new light-duty vehicle fuel economy is held constant at current levels throughout the period of the forecast. In the reference case, it improves at an average annual rate of 0.4%.

The efficiency and high-efficiency/low-carbon scenarios differ from each other less in effort than in outcome. In our view, the improvements postulated in the efficiency scenario are *likely* to be forthcoming if appropriate policy measures are undertaken and research efforts intensified. In contrast, because the outcomes postulated in the high-efficiency/low-carbon scenario require technological breakthroughs, they require a certain degree of luck to be achieved by 2010. There are no credible methods to accurately gauge the probability of such breakthroughs; we believe they stand a decent chance of occurring with an intensification of research efforts, but we stop short of claiming that they are a likely outcome of such an intensification. In other words, the efficiency scenario represents what is often called a "most likely" or "probable" scenario, in the authors' judgment. The high-efficiency/low-carbon scenario is better described as an "optimistic" or "possible" scenario. However, both are predicated on a major intensification of R&D effort plus significant policy measures aimed at pushing the market towards giving fuel efficiency a much higher priority.

The efficiency scenario is created by assuming earlier introduction of advanced fuel economy technology and by adding certain key technologies that are absent from the AEO97 reference case. It assumes the introduction of advanced ethanol-from-biomass technology in 2005, technology which the U.S. DOE is currently intensively involved in developing. In the efficiency case, technology development is incremental rather than revolutionary. Nonetheless, the efficiency case does presume a major energy technology R&D effort, perhaps two to ten times the level of current government programs. It also assumes that policies necessary to draw energy-efficiency technology into the market are implemented, as needed. In other words, effective policy actions, whether they be increased fuel economy standards, revenue neutral feebates, fuel taxes, public information or some other initiative, are assumed to have been put in place. This point is critical, because AEO97 forecasts inexpensive, plentiful fossil fuels, and because the goal of preventing global climate change is a classic public good that markets on their own will generally ignore.

Overview of Methodology

Producing scenarios for this analysis comprised three principle steps: (1) developing assumptions about future advances in energy technology for transportation, (2) entering these assumptions into an integrating model to predict their market acceptance and impact on transportation energy use and, (3) adjusting the model's predictions for analyses and forecasts done "on the side." Because of time and budget constraints, no attempt was made by the transportation sector team to integrate our scenarios with those of other energy-using sectors to produce an economy-wide scenario. The methodology is therefore a partial analysis of the effects of technology on the transportation sector, assuming no interaction with other sectors of the economy.

Obviously, there is no sure way to predict the evolution of technology. Thus, the key to developing a useful technology scenario is clearly documenting assumptions, and also demonstrating that the assumptions are consistent with recent advances in technology by referencing published scientific and technical reports. Wherever possible, we base our assumptions on objective technology assessments, such as the Office of Technology Assessment's (1995) examination of the potential for advanced automotive technology. The result of this step is a list of specific technologies with the following data for each, (1) date of initial market introduction, (2) quantitative impact on energy efficiency (e.g., % fuel economy improvement over a baseline vehicle) and, (3) incremental cost to the buyer.

We used the Energy Information Administration's (EIA's) National Energy Modeling System (NEMS), Transportation Sector Model as a tool for integrating the technology assumptions and predicting their impact on energy use. NEMS is undoubtedly the most fully documented (U.S. DOE/EIA, 1994; 1995a, 1995b, 1996a, 1996b), most rigorously peer reviewed (e.g., NRC,) and most thoroughly tested comprehensive, national energy model. The NEMS Transportation Sector Model comprises a set of submodels for each transport mode that range in complexity from the highly detailed light-duty vehicle model to much simpler models for waterborne transport and rail freight.

The NEMS light-duty vehicle model requires an itemization of each technology, as well as its applicability to each of six passenger car and six light truck classes. In addition to introduction date, cost and fuel economy improvement potential, interactions (incompatibilities, complementarities, etc.) among technologies must be carefully specified. NEMS predicts market penetration over time based on cost-effectiveness and time since introduction, but also by applicability and interactions with other technologies. These predictions reflect normal requirements for testing of new technologies, as well as turnover of the stock of manufacturing capital. The Freight Truck and Air Travel Models also require a list of technologies, introduction dates and efficiency improvement estimates, but market penetration is handled somewhat more mechanistically. In both cases, new technologies are introduced when the price of fuel crosses a threshold price. For Rail Freight and Waterborne Freight, one must directly specify a rate of efficiency improvement.

Given technology assumptions, other macroeconomic inputs, and the energy and economic predictions of the 1997Annual Energy Outlook Reference Case Projection, the NEMS Transportation Model predicts new vehicle sales, used vehicle scrappage, vehicle utilization, and fuel consumption by model and vehicle type. These endogenous predictions are sensitive to economic variables. For example, improving energy efficiency will result in some degree of increased vehicle travel due to the lower cost of fuel per mile. Based on the composition of demand by fuel type, NEMS also forecasts carbon emissions, as well. For the largest transport modes, the evolution of vehicle stocks over time are explicitly calculated in great detail. In general, the technological characteristics of a vehicle are determined in the year in which it is manufactured. NEMS then exhaustively accounts for the numbers of vehicles by type, class, and vintage, as well as which technologies have been applied to these vehicles. As a result, NEMS's representation of the dynamics of technological change are quite meticulous.

Finally, two parts of the scenario analysis were done "off line" thus necessitating some straightforward adjustments to the NEMS forecasts. The estimation of market supply and demand for cellulosic ethanol as a blending component of conventional gasoline was calculated by means of a spreadsheet model. The supply and demand studies upon which this analysis were based were simply too recently produced (they are based on draft reports) to have already been incorporated by the EIA into the NEMS model structure at the time. Also, we chose to introduce advanced direct injection diesel passenger cars and light trucks using the NEMS model algorithm for conventional gasoline vehicles rather than as alternative fuel vehicles. This reflects our belief that the new advanced diesels will be almost indistinguishable from gasoline vehicles from the consumers' perspective (with the exception of their cost and fuel economy, variables the NEMS model takes into account). A drawback of this choice is that we sacrificed the NEMS model's ability to automatically account for the additional diesel use and, therefore, had to adjust for it after the fact. Several additional calculations were made based on NEMS outputs. The NEMS model's output includes the market penetration of each technology by vehicle type and class. Using this information together with the input assumptions about technology costs and fuel economy improvement we were able to compute measures of the overall cost-effectiveness of the sum total of all technologies applied to passenger cars and light trucks.

The high-efficiency/low-carbon case begins with the efficiency case assumptions and then goes beyond incremental technological advances and postulates breakthroughs in fuel cell technology for light-duty vehicles, as well as major aerodynamic and engine efficiency gains for commercial aircraft, among other selected technological achievements. It also includes more optimistic assumptions about biomass ethanol production costs. It is not the intent of this scenario to include all possible technological advances, but rather to focus on a few that could have major long-run implications for greenhouse gas emissions from the transportation sector. We could, as well, have assumed technological breakthroughs for battery-electric or compressed or liquefied natural gas vehicles, both of which have some potential to reduce carbon emissions compared to petroleum-based fuels. The more breakthroughs one assumes, however, the lower the probability that the scenario will actually occur. Furthermore, in the long-run, no single technology appears to have a greater potential to reduce carbon emissions from transportation than the fuel cell. We do not assume a target and tradeable permit system equivalent to $50/T of carbon in the high-efficiency scenario. We do assume in both scenarios that significant policies similar to this are in place to encourage producers to produce and consumers to choose fuel-efficient, low-carbon technologies.

Although the focus of this study is on the year 2010, forecasts to 2015 are also presented because changing the technology of transportation energy use takes more than one decade. Once a technology is market ready, two to three years of testing and certification are still required prior to introduction. Even then, most technologies will not appear on all makes and models simultaneously due to the need to replace plant and equipment in an efficient manner. Finally, expected lifetimes for transportation vehicles are counted in decades. The median expected lifetime of a passenger car is now 14 years, truck lifetimes average 16 years, marine vessel and aircraft life expectancies are at least twice that (Davis and McFarlin, 1996, Tables 3.6 and 3.7). Thus, the full impact of technologies introduced between now and 2010 will not be apparent in 2010. We include the year 2015 to illustrate this fact. In all cases, a normal rate of replacement of capital stock is assumed, both in the production of transportation vehicles and in their purchase and scrappage. That is to say, no changes are made to the NEMS model to accelerate the turnover of capital stocks.

Results of the three scenario projections are compared with EIA's AEO97 projections in Table 5.1. In the business-as-usual case, transportation energy use grows from 25.5 quads in 1997 to 32.3 quads in 2010 and to 34.0 quads in 2015. Emissions of carbon increase as well, up 26% in 2010 and 33% higher by 2015. The efficiency scenario achieves roughly a 10% reduction in energy use and a 12% reduction in transportation sector emissions versus the business-as-usual case by 2010. Reductions in 2010 versus the AEO97 reference case are slightly less, 7% for energy and 9% for carbon emissions. Use of cellulosic ethanol as a blending component in gasoline reduces greenhouse gas emissions by 2-3% over and above the reduction in energy use. The greatest reductions in fossil fuel use are achieved by rail freight (-16%), light-duty highway vehicles (-12%), and commercial air travel (-11%). Energy use in 2015 is actually below that of 2010 in the efficiency scenario because of the greater penetration of new, efficient equipment into the stocks of transportation vehicles. Transportation uses 28.2 quads of energy, 17% below the business-as-usual case but still 10% over 1997 levels. Emissions of carbon are down by 20% over the business-as-usual case, still 6% higher than in 1997. The high-efficiency/low-carbon scenario reduces energy use and carbon emissions by another 4% in 2010 and by an additional 5% in 2015. By 2015, transportation sector carbon emissions are projected to be below the 1997 level in the high-efficiency/low-carbon scenario.

Table 5.1 Comparison of Three Transportation Energy Scenarios to the AEO97 Reference Case

Energy Use (quads)	1997	2010	2015
Business-as-Usual	25.5	32.3	34.0
Reference Case	25.4	31.4	32.3
Efficiency	25.4	29.2	28.6
High-Eff/Low-Carbon	25.3	27.8	26.4
Carbon Emissions (MtC)	**1997**	**2010**	**2015**
Business-as-Usual	487	616	646
Reference Case	485	598	614
Efficiency	485	543	532
High-Eff/Low-Carbon	484	513	485

Note: Carbon emissions include emissions from the generation of electricity for electric vehicles. Reference case assumptions about electric vehicle market penetration have not been changed in any of the three scenarios. Similarly, transportation energy use includes electricity generation losses.

We wish to emphasize that, in our judgment, the reductions in carbon emissions described in these scenarios are unlikely to be achieved by advances in technology alone, in the absence of meaningful additional policy measures to insure that cost-effective and near cost-effective technologies to improve energy efficiency and to expand the production of biomass fuels are in fact implemented. This is not only our conclusion. The 1995 Asilomar Conference on Energy and Sustainable Transportation, organized by the National Research Council (NRC), Transportation Research Board's Committees on Energy and Alternative Fuels, addressed the question, "Is technology enough to achieve sustainable transportation?" The conference's consensus, to be published in a forthcoming volume of proceedings, was that technologies capable of creating a sustainable transport system could be developed over a reasonable time period but that the marketplace on its own would be unlikely to adopt such technologies in the absence of specific policy measures to make it happen (McNutt et al., 1997). Because of the inertia inherent in the nation's transportation system, and because reducing greenhouse gas emissions is a public good, meaningful policy action is likely to be essential to achieving the carbon emissions reductions described in these scenarios.

We also believe that research and development of low-carbon emission technologies will have to be expanded to achieve the results of the efficiency and high-efficiency scenarios. Support for this view can be found in the NRC's just-published review (NRC, 1997) of the research program of the PNGV, the most significant national effort to advance technology to improve transportation energy efficiency. The views of the standing committee charged with reviewing the progress of the program are unambiguous:

> "The PNGV is experiencing severe funding and resource allocation problems that will preclude the program from achieving its objectives on its present schedule if they are not resolved expeditiously."

The panel comments on the serious underfunding of PNGV in at least nine different places in its report. In Table H-1, summarizing its assessment of the status and prospects for the key PNGV technologies, all technologies save fuel cells were categorized as having a basic need for additional resources. Noting that PNGV has been unresponsive in providing the committee with estimates of the funding that would be required, the committee notes that the industry consortium of the PNGV stated that it would like to see government funds available to PNGV doubled (NRC, 1997, p. 107). Elsewhere, the committee notes that funding for ultracapacitor research would have to be increased by at least ten times for a period of 10 to 15 years in order to catch up with the status of battery research with respect to PNGV goals. While the technological progress assumed in our efficiency case does not require that PNGV goals are attained, continued advances by industry and government R&D programs will be essential. PNGV, of course, addresses only light-duty vehicles. R&D support for low-greenhouse gas technologies for other modes is even more modest. In the view of the transportation sector analytical team, substantial additional funding for R&D will be required, perhaps two to ten times what is presently being spent, depending on the area of investigation.

5.2 PROVEN AND ADVANCED TECHNOLOGIES

Despite the fact that the fuel economies of successive model years of U.S. new cars and light trucks have been essentially constant for the past decade (Heavenrich and Hellman, 1996), technologies positively affecting vehicle efficiency have continually entered the fleet. These include fuel injection, 4-valve per cylinder engines, 4-speed electronically controlled automatic transmissions with lockup, growing use of lightweight materials and structural redesign for weight reduction, tires with lower rolling resistance, and improved aerodynamics. Efficiency improvements offered by these technologies have been counteracted, however, by increased acceleration performance and top speed; weight increases due to increased body stiffness and more power and safety equipment (e.g., air bags); and other factors. In other words, auto makers and purchasers have been willing to trade off fuel economy for competing vehicle amenities such as weight and power.

There is wide agreement that new efficiency technologies will continue to enter the fleet, and that technologies recently entered will gain market share. Table E.1 in Appendix E lists those technologies that appear in the NEMS data base and are expected to either gain market share or enter the market during the next decade or so. With a few exceptions, these are proven technologies whose costs and impact on efficiency can be reliably specified. The most important of these technologies, from the standpoint of their potential impact on fleet fuel efficiency during the next few decades, are described briefly below. Documentation for costs and projected fuel efficiency improvements for these and the other technologies in the NEMS data base is contained in Energy and Environmental Analysis, Inc. (1994).

5.2.1 Material Substitution

Weight reduction has been a key factor in the U.S. automobile fleet's fuel economy improvement since the early 1970s, and will likely play an important role in future improvements. Past weight reductions involved a combination of a widespread conversion to front-wheel drive, which eliminated the drive shaft and rear axle and allowed important packaging gains; a significant downsizing of the fleet, made possible by changing consumer demands; the shift to unit body construction from a chassis on frame structure; and material substitution, largely from plain carbon steel to high strength low alloy (HSLA) steels, but also including shifts to plastic parts and some aluminum as well. Recently, structural redesign using supercomputers has allowed significant weight savings. However, much of these savings have been taken back by increases in body rigidity, which enhances ride quality and safety, as well as the addition of safety and power equipment. Accordingly, the average weight of the fleet has begun to increase.

Despite past improvements, there remain substantive possibilities for large weight reductions without sacrificing vehicle interior space or safety. The Office of Technology Assessment (U.S. Congress, OTA, 1995)[2] identified an array of weight reduction scenarios including the following: a "clean sheet" design using advanced steel alloys that might achieve greater than a 10% weight reduction in a mid-sized auto; all-aluminum vehicles using successively more optimized designs achieving up to a 30% reduction; and a technically-optimistic design using polymer composites achieving a 35-40% reduction (though OTA considered this last scenario to be quite uncertain from a commercial standpoint because it requires breakthroughs in manufacturing technology).

Material substitution is treated in a series of steps in the NEMS model, with each step representing a 5% weight reduction relative to the baseline. The first step (now complete in the current new car fleet) represents increased use of HSLA, while the next four steps represent increasing use of plastics and aluminum over time, to achieve a total reduction of 20% relative to a modern 1990 vehicle (more with older non-unit body designs).

5.2.2 Aerodynamic Drag Reduction

Improvements in vehicle aerodynamics have been an important part of the overall fuel economy improvement of the U.S. light-duty vehicle fleet, with average drag coefficients (C_ds) being reduced from 0.45-0.50 in 1979/1980 to between 0.30 and 0.35 today, with some models in the 0.27-0.29 range. These reductions are important to vehicle fuel economy because a 10% reduction in C_d typically will yield a 2.0-2.5% increase in fuel economy at constant performance.

Prototypes with extraordinarily low C_ds (e.g., 0.18 for the Chevrolet Citation IV and 0.15 for the Ford Probe IV ("Going with the Wind," 1984)) have been shown, and the General Motors EV1 electric car attains a C_d of 0.19. There is a strong consensus among auto makers, however, that mass market vehicles will likely be limited to C_ds of about 0.25 because of limits on the practical slope of windshields, need for cargo space (low C_ds require tapered rear ends), and other factors, including customer design preferences. Further, reductions in C_ds for light trucks are limited by factors such as need for high ground clearance and large tires, open beds in pickup trucks, and so forth. Also, the short length of subcompact autos limits the degree to which their C_d can be reduced.

In NEMS, aerodynamic drag reduction is also implemented in a series of steps starting from a 1990 C_d baseline of 0.37, with each step representing a 10% reduction over the previous level (i.e., to 0.33, 0.30, 0.27, and 0.245, respectively).

5.2.3 Improved Automatic Transmissions

A range of potential improvements to automatic transmissions can offer fuel economy benefits of up to about 6% in automobiles. Key areas of improvement are design changes that reduce hydraulic losses in the torque converter and transmissions with added numbers of gears, with continually variable transmissions possible.

Five-speed automatic transmissions were introduced in Japan and Europe a few years ago and have recently been introduced to the United States in a few luxury models. Nissan and Mercedes have experienced fuel economy gains over a 4-speed automatic in the 2–3 MPG range (Hattori et al., 1990). A number of continuously variable transmissions (CVTs) have been tested with widely varying results, and Suburu sells a small car with a CVT in the U.S. market. OTA estimates that a CVT should be capable of achieving approximately a 6% fuel economy increase over a 4-speed automatic.

Electronic transmission control of both conventional automatic transmissions and CVTs will add some benefits over the older mechanical controls. First generation controls selected only the shift points and provided about 0.5% benefit in fuel economy, and such controls were in most transmissions by 1995. More advanced second generation controls have appeared, and they interact with the engine control to optimally select torque converter lock-up and shift points while also determining engine calibration. Such controls provide 1.5% benefit over mechanical controls.

5.2.4 Engine Friction Reduction

Reducing mechanical friction is an ongoing process in engine development, and steady reductions in friction have occurred as engine designers continually modify existing engines and introduce new engine families. There is substantial potential for fuel economy gains as existing friction reduction improvements are rolled into the fleet. Primary areas for further improvement are:

- Piston and connecting rod weight reduction using lightweight materials,
- Lightweight valves and valve springs,
- Use of two rings instead of three,
- Improved oil pumps,
- Improved lubricants,
- Low friction crankcase seals, and
- Roller cam followers.

Only roller cam followers and two-ring pistons are discrete technologies, with specific benefits of 2% in fuel economy, while other benefits are based on design evolution.

Fuel economy improvements of as much as 4.5% (compared to current engines) should be available using the full range of evolutionary technologies. The NEMS model has separate representation of roller cams, while all other technologies are modeled as engine friction reduction in discrete steps of 1.5% benefit in fuel economy, with steps in the order of increasing cost and complexity.

5.2.5 Variable Valve Timing

In conventional engines, the timing and extent of opening of the intake and exhaust valves are fixed, and are compromises between the very different needs of high and low power settings. Variable valve control allows substantial efficiency improvement; for example, closing the intake valves early can substitute for throttling to reduce air intake, thus reducing pumping losses at low load. Also, variable valve control boosts engine power, allowing engine downsizing while maintaining power levels.

Honda uses a system called VTEC that controls both lift and timing of intake and exhaust valves. VTEC is not a fully variable system, offering only two settings for valve timing and lift, but it still obtains an 8% fuel economy improvement at constant performance. It has been used in the U.S. market both for boosting power (Acura NSX, Prelude VTEC) and improving fuel economy (Civic VX).

Although VTEC was introduced to the U.S. market in 1991 (in the NSX), neither VTEC nor competing systems (Mitsubishi uses a system, MIIVEC, that combines valve control with cylinder shutdown at low loads) have gained significant market share since then. The major concerns are cost and complexity. Second generation VVT systems that offer wider control of lift and timing are expected to increase fuel economy benefits at constant performance to 10%.

5.2.6 Lean-Burn Engines

Lean-burn engines reduce engine power by reducing fuel flow without throttling back airflow, thus increasing the air/fuel ratio; in contrast, conventional engines maintain air/fuel ratios at or below "stoichiometric" (i.e., the ratio – about 14.6:1 – where there is just enough air to fully combust the fuel). Aside from the reduced pumping loss obtained by foregoing throttling, engine thermal efficiency is increased and hydrocarbon and carbon monoxide emissions are reduced. The primary challenges facing lean-burn engines are difficulties in maintaining stable combustion at high air/fuel ratios and the need to develop new NO_X catalysts that will work in an oxygen-rich exhaust environment. The former challenge generally is handled by designing the cylinder/piston/valves/fuel injector system and operation in such a way as to stratify the fuel charge so the region around the spark plug has a richer fuel mixture than in the rest of the combustion chamber and ignites readily. An alternative method is to use high swirl combustion chambers that promote combustion. For the emissions challenge, most automobile manufacturers are working to develop "lean NO_X catalysts," and, as discussed below, both Toyota and Mitsubishi have sold vehicles that combine lean operation and new NO_X catalyst technology since the early 1990s in Japan.

Low cost lean-burn systems that do not need "direct injection" of fuel into the cylinder head can provide up to a 10% benefit in fuel economy by utilizing advanced cylinder head designs and lean air-fuel sensors.

5.2.7 Advanced Tires

Rolling resistance accounts for approximately a third of the loads on an automobile during the EPA test procedure. The magnitude of this resistance is approximately linearly related to the rolling resistance coefficient of the vehicle's tires, so reducing this coefficient through changes in tread design, tire materials, and tire structure will have a significant positive impact on fuel economy.

Tire design and materials have improved steadily throughout the years, with the switch to radials from bias-ply tires beginning in the late 1970s, then the shift to second generation radials beginning in the mid-1980s each achieving about a 20-25% reduction in rolling resistance and a 3-4% improvement in fuel economy.

Additional improvements have recently been introduced by Michelin and other companies and are beginning to penetrate the fleet. Use of these and other, further-improved designs can yield about a 25% reduction in rolling resistance by 2005, with 5% improvement in fuel economy resulting; an additional 3% fuel economy improvement may be possible by 2015 (Hattori et al., 1990). Some of these gains are likely to be offset by manufacturer design decisions that increase tire traction and durability, so that only about half the potential fuel economy gains are likely to be realized. The NEMS model has the improvements occurring in four discrete steps over time to achieve a total 4% benefit in fuel economy.

Aside from these proven technologies, there are a few additional technologies that are not expected to enter the fleet in commercially significant amounts before 2010 under the business-as-usual case assumptions, but that have the potential to impact fleet fuel economy in this time frame if there are appropriate incentives. These are:

- Advanced drag reduction (to a C_d of 0.22 for mid-sized vehicles),
- Hybrid-electric power trains,
- Direct injection stratified charge (DISC) gasoline engines,
- Direct injection (DI) diesel engines, and
- Proton exchange membrane (PEM) fuel cell power trains.

All but the PEM fuel cell power trains are considered likely to be introduced into the U.S. in small numbers before 2010 (e.g., in limited edition or luxury models). In fact, Volkswagen has already introduced DI diesel engines into the U.S. market as options in its Passat, Jetta, and Golf models. DI diesels cannot meet current NOx standards for gasoline-fueled automobiles. At this time, diesels have an exemption to U.S. rules on NOx emissions; however, this exemption is unlikely to stand if large numbers of diesels are sold in the U.S. market. Similarly, DISC engines have been introduced into the Japanese fleet by Toyota and Mitsubishi, but their high cost and U.S. emissions requirements should keep them out of the U.S. fleet for the immediate future – except perhaps in very limited numbers. As discussed below, however, these technologies could make an impact on U.S. fleet fuel economy before 2010 either in the efficiency scenario, which postulates both increased R&D spending and increased market or regulatory incentives for fuel economy, or in our high-efficiency/low-carbon scenario that postulates better-than-expected luck in technology development.

5.2.8 Advanced Drag Reduction

In our view, significant market pressure on fuel economy could reduce C_d values a bit further than projected by the auto makers. Some existing vehicle designs that have attained lower C_ds without some of the design compromises of the prototypes noted above indicate that a C_d of 0.22 should be practical for a mid-size car without requiring wheel skirts or a sharply tapered rear end.[3] This value has been adopted as successfully entering the mass market automobile fleet in both the efficiency and high-efficiency/low-carbon scenarios, and is modeled as an additional 10% reduction in drag over the lowest C_d value in NEMS of 0.245.

5.2.9 Hybrid-Electric Power Trains

Hybrid-electric power trains combine two energy sources with an electric drivetrain, with one or both sources providing electricity to the electric motor. Although many configurations are possible, all have some form of energy storage (battery, flywheel, ultracapacitor, etc.). Hybrids offer a theoretical efficiency advantage over conventional internal combustion engine (ICE) drivetrains for the following reasons:

- They offer the potential to recapture some of the vehicle's potential energy that is normally lost (as heat) when the vehicle is braked. In a hybrid, the electric drive motor can be operated in generator mode to brake the vehicle; the electric energy produced is stored in the battery or other storage device.
- The hybrid drivetrain allows the vehicle powerplant to be smaller and to operate more efficiently than the powerplant in a conventional drivetrain. In a conventional drivetrain, the engine is sized for the maximum load (usually short-term rapid acceleration) and can produce many times the power it uses during the great majority of its operation. For example, during idle, low speed cruise, or deceleration, the powerplant may be operating below 10% of its maximum power capability, and most engines (especially gasoline engines) are very inefficient

at such lower power levels. Because the storage device can absorb any excess power (over that needed to operate the vehicle) produced by the engine, the engine can continue to operate at an efficient power level even when the vehicle loads are low. Also, in a hybrid, the storage device can provide part of the power for maximum acceleration, allowing the hybrid powerplant to be sized for average power requirements or for power requirements in operations where the battery can't help (e.g., during sustained hill-climbing), which are generally lower than acceleration loads – so the hybrid's engine can be smaller.

The net energy gains from the regenerative braking, smaller and lighter powerplant, and improved powerplant cycle efficiency are counteracted by losses in the electrical components (storage device, generator, motor/controller) and their added weight (in particular, weight of the storage device and electric motor). The wide variety of hybrid configurations and component designs, the relatively early stage of development of hybrid powertrain systems, and the ongoing redesign of hybrid powertrain components to satisfy the unique requirements of hybrid operation has yielded a wide range of estimates of the potential efficiency benefits of shifting to hybrid drivetrains. Further, ongoing changes in engine design for conventional drivetrains shift the relative value of hybridization, with reduction in pumping losses achieved by variable valve control, for example, reducing the benefit of hybridization because these are the same losses hybridization is designed to counter. The OTA has estimated that a battery/ICE hybrid can achieve about a 25-35% gain over a conventional drive vehicle with the same type of powerplant, assuming what it considered optimistic values for the efficiencies of the battery and electric motor (U.S. Congress, OTA, 1995). Current examples of operating hybrids that satisfy normal vehicle safety and performances requirements[4] have not achieved efficiency improvements this high (U.S. Congress, OTA, 1995). On the other hand, the Department of Energy's (DOE's) goal for its hybrid drivetrain R&D program is a doubling of fuel economy, and theoretical analyses of hybrid configurations using simulation models have projected gains ranging as high as the DOE goal (Burke, 1995; Ross, 1996). In our view, gains this high are unlikely without sacrificing some aspects of performance or operational flexibility. On the other hand, there are active R&D efforts on hybrid components such as ultracapacitors and high-efficiency electric motors that, if successful, could raise the efficiency advantage of hybridization to somewhat higher levels than OTA projects. The efficiency case conforms approximately to the OTA projections; the high-efficiency/low-carbon case assumes exceptional success at improving drivetrain components and reducing costs. This translates to a 28% fuel economy benefit over a 1995 conventional gasoline-fueled car, and a 10% benefit over a DI diesel vehicle for the efficiency case; in the high-efficiency/low-carbon case, the assumed gains are 43% and 23%, respectively.

The primary barriers to successful commercialization of hybrid-electric vehicles are the current high costs of electric motors, controllers, and batteries, and the need for additional progress in reducing the specific power and increasing the efficiency of these electrical components. In particular, there is an urgent need for reliable high-efficiency, high specific power batteries. There recently has been progress on such batteries, but considerable work remains. In addition, there are relatively few suitable engines in the right size category (one liter or so) for hybrids, since automotive engines typically are sized to meet the higher power requirements of conventional drivetrains.

5.2.10 Direct Injection Stratified Charge (DISC) Gasoline Engines

Conventional spark ignition (gasoline) engines are inefficient at part load in large part because they reduce power by throttling back on their air supply, creating large drag losses (so-called "pumping losses") in the stream of intake air. Direct injection stratified charge engines do not throttle intake air; instead, they reduce only fuel flow at part load, operating at fuel/air ratios as low as 1:50. They manage this by injecting fuel directly into each cylinder at high pressures (700 psi or higher compared to 50 psi in a conventional fuel injection system (Markus, 1997)) in such a way that the fuel/air mixture is stratified (thus, "stratified charge"), with high fuel concentrations near the spark plug so as to maintain stable combustion. The combination of zero throttling losses, low fuel use at light loads because of the very lean fuel mixture, and some added benefits of direct injection – particularly, more precise control of combustion and fewer problems such as fuel condensation on intake-port walls – yields substantial fuel efficiency improvements rivaling those of DI diesels.

Concerns with DISC engines include problems with increased NO_X emissions because normal reduction catalysts will not operate in the oxygen-rich exhaust environment of a lean-burn engine; the expense and durability of the fuel injectors, which have to operate at very high pressures ranging up to 2000 psi; and the need for extremely precise control of combustion to maintain smooth performance from the engine as it shifts back and forth between lean to stoichiometric operation.

Both Toyota and Mitsubishi have introducing DISC engines into their fleets in Japan, Mitsubishi with a 1.8 liter, 148 hp engine in its Galant sedan and Legnum wagon, Toyota with a 2.0 liter, 143 hp engine in its Carina sedan (Markus, 1997). Both companies use catalysts to reduce NO_X emissions: Mitsubishi's is a true lean-NO_X catalyst that reacts hydrocarbons with NO_X to form nitrogen, oxygen, water, and carbon dioxide; Toyota's system stores NO_X and reduces it to nitrogen during high power operation when the engine uses a stoichiometric (no excess air) air/fuel mixture (Markus, 1997). Neither system is believed ready to meet U.S. emissions requirements, especially for catalyst longevity. The Toyota system would likely experience difficulties with high levels of sulfur in U.S. fuels, which can poison the catalyst material.

Available data suggest that Toyota's DISC engine provides a 25% fuel economy benefit in the Japanese 10-mode cycle, which could translate to an 18% benefit in the U.S. FTP if emissions problems are solved. This benefit has been used in the efficiency case; in the high-efficiency/low-carbon case, a benefit of 23% is assumed.

5.2.11 Turbocharged Direct Injection (TDI) Diesel Engines[5]

Until recently, all diesel powertrains used in light-duty vehicles in the United States were indirect injection diesels (IDI). In an IDI diesel, fuel is sprayed into a prechamber, mixed with air, and partially burned before the charge is passed into a main combustion chamber where the combustion continues. This design was desirable for automobiles because it yields smoother combustion with less noise and lower NO_X emissions than direct injection designs. These advantages are purchased at the expense of some efficiency losses from heat transfer from the prechamber and pressure losses as the partially burned gases flow through the passages between the prechamber and main combustion chamber.

Advances in fuel injection technology and combustion chamber design, coupled with turbocharging and intercooling, have allowed direct injection diesels to attain smoothness and noise levels comparable to IDI diesels with low NO_X emissions and high specific power (power/weight) levels, approaching that of naturally aspirated 4-valve per cylinder gasoline engines. The best 4-valve turbocharged DI diesels can attain fuel economy improvements of 40% or more over current 2-valve per cylinder engines, though conversion to gasoline equivalent fuel economy yields closer to a 30% gain (diesel fuel is a more energy-dense fuel than gasoline). The 40% value has been used in our analysis, but it assumes that lean-NO_X catalysts will be successfully adapted to diesels to meet NO_X standards. Catalyst researchers generally are considerably less optimistic about success for diesels than they are for gasoline-fueled vehicles.

As noted above, Volkswagen has introduced DI diesels into the U.S. fleet in its Golf, Jetta, and Passat models. These engines are 1.9 liter and produce 105 horsepower. Audi produces a larger 2.5 liter engine for its European models.

5.2.12 Proton Exchange Membrane (PEM) Fuel Cell Powertrains

Fuel cells are electrochemical devices that convert the chemical energy in fuels to electrical energy directly, without combustion. This process avoids the thermodynamic limitations imposed by the Carnot cycle, and fuel cells theoretically can have efficiencies of 90% or greater. With hydrogen as a fuel, fuel cells have emissions only of water; with fuels such as methanol or hydrocarbons, reforming to obtain hydrogen will produce small quantities of carbon monoxide and other pollutants as byproducts and larger quantities of carbon dioxide.

For the immediate future, PEM fuel cells appear to be the clear choice among alternative fuel cell technologies for light-duty vehicle applications because they operate at moderate temperatures (20-120 degrees C) and developers have been able to rapidly improve their power density (from .085 kW/liter in 1989 to about 1 kW/L today) and decrease their costs (platinum loadings, a major cost factor, have been reduced from about 4 mg/cm^2 in 1990 to current levels of about 0.15 mg/cm^2) (Oei, 1997).

Despite rapid progress, fuel cells must overcome major hurdles before they can succeed commercially in the light-duty market. Costs must be sharply reduced. Even with mass production, PEM fuel cells would cost at least $200/kW to manufacture with today's production technology and cell designs – nearly ten times the cost of ICE engines (Oei, 1997), disregarding the additional cost of needed hydrogen storage or reformers.[6]

Key needs are development of low-cost membranes, size and cost reduction of hydrogen reformers or onboard storage, and improvement of "balance of plant." Also, there are several "engineering" issues that will have to be dealt with once stack design has gotten to the point where serious vehicle design is contemplated – for example, cooling (the low temperature operation of fuel cells means that the heat being rejected is very low grade heat, requiring lots of air movement or large radiator surface areas, neither very appealing to vehicle designers (Borroni-Bird, 1997)) and prevention of freezing in cold weather.

On-board fuel storage represents a significant barrier because hydrogen's energy density is very low,[7] and the easiest fuel to reform into hydrogen onboard the vehicle, methanol, has no significant supply infrastructure. Chrysler in partnership with DOE recently announced significant progress towards onboard production of hydrogen from gasoline, which would solve the supply infrastructure problem and allow much easier fuel storage than hydrogen. Not surprisingly, however, the selection of gasoline as the preferred "hydrogen carrier" for fuel cells is by no means an easy call. For example, gasoline's availability and easier fuel storage must be traded off against the cost and space occupied by the reformer (Jost, 1997).[8] Toyota has claimed a substantial improvement in hydrogen storage technology using an advanced metal hydride adsorbent that matches the energy density of liquefied hydrogen storage with only 10 atmospheres of pressure required (Yamaguchi, 1997). Presumably, however, this type of storage would be extremely heavy. Other options being pursued by various researchers include direct methanol fuel cells, which preclude the need for a reformer, and the use of ethanol in place of methanol or gasoline as a hydrogen source. The latter option is especially attractive if the ethanol can be produced from cellulosic materials, because the effect on reducing greenhouse gas emissions is particularly large for this technology.

We expect the rate of progress and probability of commercialization of fuel cell powertrains to be sensitive to the level of R&D funding and market pressures to improve overall vehicle fuel economy. Progress has in fact been rapid, as shown by the improvements in power density discussed above. Ford, GM, and Chrysler are all pursuing fuel cell vehicle R&D, as are Japanese and European companies, with Toyota's and Mercedes Benz's programs being the most visible. A Canadian company, Ballard, appears to be in a leading position in PEM fuel cell R&D, and has supplied systems to most of the vehicle R&D programs. Given current funding levels and the market's lack of pressure on fuel economy levels as well as the large amount of development work that remains to be done, however, introduction of fuel cells into mass market vehicles appears likely to be beyond the 2010 time frame, and the base scenario adheres to this projection. This, in fact, was the conclusion of the NRC's advisory panel overseeing the PNGV program (NRC, 1997, Table H-1). On the other hand, increased funding and market pressure and/or particularly fortuitous progress in the ongoing R&D program might move the date of introduction forward. Further, the newness of the technology and the dependence of the basic fuel cell stack costs on manufacturing design leaves open the potential that the eventual cost of the fuel cell system might be somewhat lower than competing ICE drivetrains; this depends on substantial cost reduction over a range of technologies, because the costs of hydrogen storage or reforming, the electric motor, and even the battery that is likely to be necessary for startup power, all play a significant role in total system costs.

The efficiency case assumes that fuel cells will not be introduced in mass market vehicles before 2010; we note that the major auto makers are not projecting a pre-2010 commercial introduction of fuel cell vehicles even assuming a high level of success in their development programs. The PNGV program envisions that the earliest fuel cells will use a reformer to produce hydrogen from gasoline. We assume that fuel cells in conjunction with a gasoline reformer will be about 70% more efficient than current gasoline engines, but only slightly more efficient than a diesel hybrid drivetrain. The high-efficiency/low-carbon case assumes introduction of commercial gasoline fuel cell vehicles by 2007. Although ethanol from cellulosic material would make an excellent fuel for the fuel cell hybrid and would result in further reductions in greenhouse emissions, we assume the first fuel cell vehicles will use widely-available gasoline.

5.2.13 Fuel Cells in Heavy Trucks and Locomotives

In many ways, fuel cell propulsion may be attractive for large transportation vehicles, such as locomotives or ships, before it is ready for use in light-duty vehicles. Use of fuel cells in heavy trucks will require a breakthrough in hydrogen production, distribution, or on-board storage, or else a breakthrough in reforming technology before it will be competitive with the diesel engine. The drive-cycle thermal efficiency of current heavy-duty diesel truck drivetrains is in the range of 35% to 40%. The drive-cycle thermal efficiency of current methanol steam-reforming fuel cell drivetrains (including electric motor/controller and battery) is also 35% to 40%. Thus, there is likely to be little incentive for heavy trucks to switch to fuel cells until hydrogen fuel cells, with drivetrain efficiencies in the range of 45% to 50%, become available.

Fuel cells may succeed in the locomotive market first because, (1) fuel costs are more important to rail carriers than to truckers, (2) locomotives already use electric traction drive and, (3) fuel cells of the size necessary for locomotive powerplant output (4000 HP) are already commercially viable in stationary powerplant applications. Therefore, we consider the use of fuel cells in locomotives in the high-efficiency/low-carbon scenario. Fuel cells may also have applicability to marine vessels, again because of their size. We do not introduce marine fuel cell applications in the high-efficiency/low-carbon technology scenario, simply because we are not aware of suitable applicability studies. We believe that analysis of the potential for fuel cell technology in heavier transportation vehicles would likely reveal additional promising applications. Thus, the locomotive fuel cell analysis is intended more to be indicative of potential large-scale fuel cell applications in transportation than a reflection of our judgment of the true potential market.

Locomotives can be broadly classified into two types: local service and line haul. Local service locomotives are primarily older line-haul locomotives that are low powered (2000-3000 HP), and are typically utilized in light load applications. Local service locomotives consume about 120,000 gallons/year of fuel per locomotive. Line-haul locomotives are more powerful (4000 HP) and consume 375,000 gallons/yr of fuel per locomotive. Both types spend considerable amounts of time at idle, over 70% of the time for local service locomotives and over 50% of the time for line-haul. Idle fuel consumption accounts for 38% of fuel consumed in local service locomotives, and only 6.3% of fuel consumed for line-haul locomotives (CARB, 1991; CARB, 1992).

Locomotives have very long useful lives and the engines are rebuilt several times. The diesel engine alone costs about $400,000, but a complete rebuild costs only about $100,000 to $150,000. Engines are typically rebuilt every eight years, and the entire locomotive is rebuilt every 24 years and/or moved to local service at that point. Hence, a useful life calculation of 24 years may be reasonable in terms of a replacement cycle.

A fuel cell based locomotive could utilize methanol, ethanol, or liquefied natural gas (LNG) and could be of the PEM type being considered for cars or the Phosphoric Acid type used for power generation. It is believed that for high power applications, the Phosphoric Acid Fuel Cell is in a relatively greater state of maturity. Several large units are currently operating as prototypes for power generation. Estimates of future fuel cell costs are highly uncertain, but megawatt size Phosphoric Acid units could be manufactured at low volumes for approximately $1000/kW in the near future, and perhaps at $400-500 per kilowatt in ten years. At this cost, a typical locomotive unit of 3000 kW would cost $1.2 to $1.5 million in 2007 reflecting a cost premium of $800,000 to $1.1 million over a diesel engine powered locomotive. It is also possible that "rebuilds" would not be required every eight years so that net cost differences may be smaller over the lifetime of the locomotive. Also, developers of PEM cells for highway vehicles are aiming at sharply lower costs, in the range of $50 per kilowatt (for the fuel cell only) or lower; although the size, duty cycle, and manufacturing volume of locomotive and automotive power plants are clearly very different, presumably a portion of any cost reductions achieved in automotive fuel cells would be applicable to fuel cells designed for locomotives.

The average efficiency of the fuel cell over the duty cycle would be 1.6 to 1.7 times as high as the diesel engine (whose cycle average efficiency excluding idle is about 35%). Fuel savings of 40% are possible, which is approximately 150,000 gallons/year for a line-haul locomotive. Hence fuel savings alone could pay for the capital cost increases over about eight years, making the technology reasonably cost-effective in the context of a 24-year useful life. Of course, major uncertainties exist in the actual cost of the fuel cell for a 3000 kW unit, the life of the fuel cell, and the maintenance requirements relative to a diesel engine.

If successful, fuel cell locomotives could have a 5 to 6% market share by 2010, and 16 to 18% by 2015, for the total fleet. In the high-efficiency/low-carbon scenario, we assume a 5% share in 2010 and 20% by 2015. We further assume use of cellulosic ethanol, although methanol and LNG would also be likely candidates.

5.2.14 Costs and Timing of Technology

As part of the OTA study, the cost of all the above-described automotive technologies was derived on the basis of near-term estimates, though at high production volume. One possible area for improvement in costs is the effect of research and additional learning to provide an "experience" based cost reduction. Lipman and Sperling (1997) have analyzed cost reductions based on cumulative total production, and concluded that many new technologies experience a 20 to 35% cost reduction for every order of magnitude increase in cumulative production (i.e., the cost decline function is linear with respect to the logarithm of cumulative units produced). If these new technologies are manufactured at typical automotive volumes from their introduction, then an order of magnitude increase in cumulative production will occur over a span of five to seven years with sales growth over the period. The next order of magnitude increase in cumulative production will take much longer unless the technology essentially increases market share to 100% over the next decade. We have utilized the data from the Lipman and Sperling paper to conclude that a 30% cost reduction over the 1997-2005 period is possible relative to the costs derived for OTA.

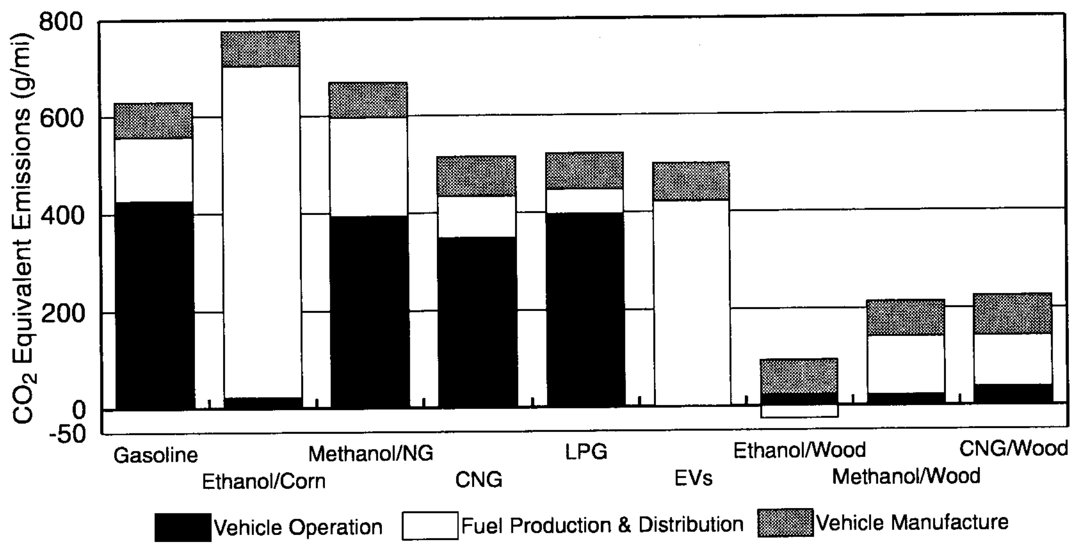
A second factor is the timing of technology introduction. The contrast here is between new technology introduction in a business-as-usual scenario relative to one where both business and government invest in research and development at rates consistent with an accelerated PNGV, coupled with changes in market preferences for fuel economy driven also by changes in government policy (e.g., new fuel economy standards, high motor fuel taxes, etc.). The resulting reduction in lead time is assumed to be 30% relative to the earliest introduction dates forecast by OTA, starting from 1997. In other words, a technology forecast by OTA to be commercialized in 2010 (13 years from 1997) would be expected to arrive in 2006 (1996 + [13*0.7]) under the regime of increased R&D spending and market changes. This factor has been incorporated for all post-2005 technologies defined in NEMS or added to the NEMS technology list for the efficiency and high-efficiency/low-carbon cases.

5.2.15 Alternative Transportation Fuels

Alternative Fuels derived from fossil energy sources have limited potential to reduce greenhouse gas emissions. The full fuel cycle greenhouse gas emissions of fossil fuels have been compared in detail by Delucchi (1991, Tables 9a-e), Wang (1996) and others. Several fossil fuel alternatives have somewhat lower CO_2 emissions than conventional or reformulated gasoline (RFG), most notably liquefied petroleum gases and natural gas, whether compressed (CNG) or liquefied (LNG). On the basis of emissions of CO_2 equivalent greenhouse gases per vehicle mile, CNG and LPG offer moderate reductions both for light (Figure 5.1) and heavy-duty (Figure 5.2) vehicles. Methanol from natural gas, while it is a relatively attractive alternative fuel for spark-ignited internal combustion engines, seems to offer no CO_2 reduction potential.

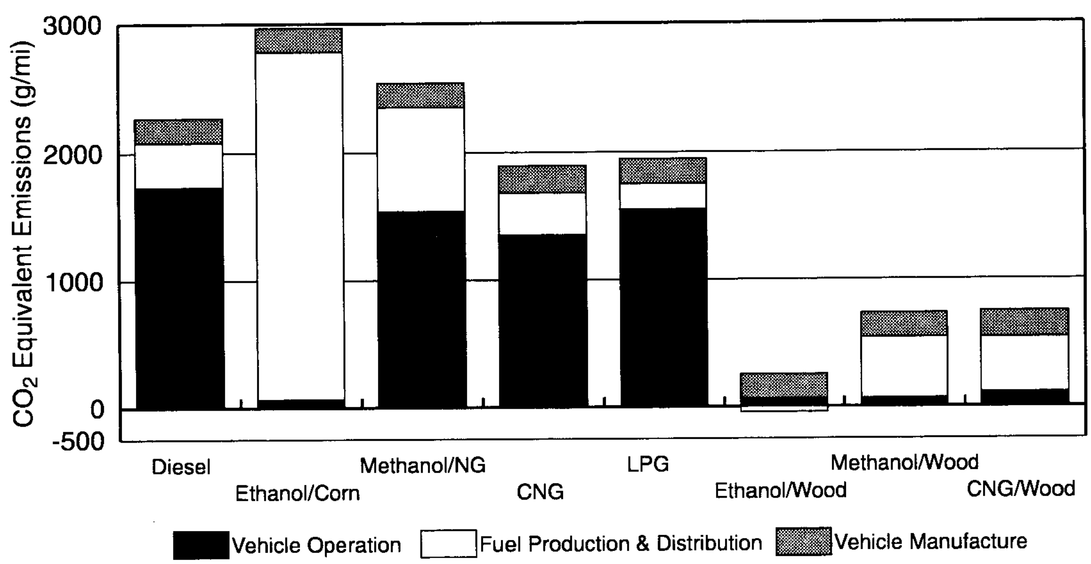
Battery-powered electric vehicles (EVs) can also lower greenhouse gas emissions, depending on the energy source used to produce the electricity stored in the vehicle's batteries. Electricity obtained from nuclear or solar power would very nearly eliminate greenhouse gas emissions. Use of nuclear power is unlikely, however, since nuclear power plants tend to operate at capacity at present and are not likely to supply a marginal increase in demand due to electric vehicle use. Electricity from current natural gas-fired plants would achieve roughly a one-third reduction, and electricity from advanced combined cycle natural gas generations could do even better. Estimating CO_2 emissions reductions from electric vehicles is highly dependent on assumptions about when vehicles will be recharged and how utilities will choose to operate different kinds of generating units. One such set of estimates, developed based on technologies and generation mixes projected for 2015, is shown in Figure 5.3. There are no CO_2 emissions from vehicle operation and emissions from vehicle manufacture are the same for all regions. Largely due to greater use of natural gas in advanced generating units, the south central and west regions are expected to produce the lowest greenhouse gas emissions for EVs operated there.

Figure 5.1 Fuel Cycle Greenhouse Gas Emissions for Light-Duty Vehicles



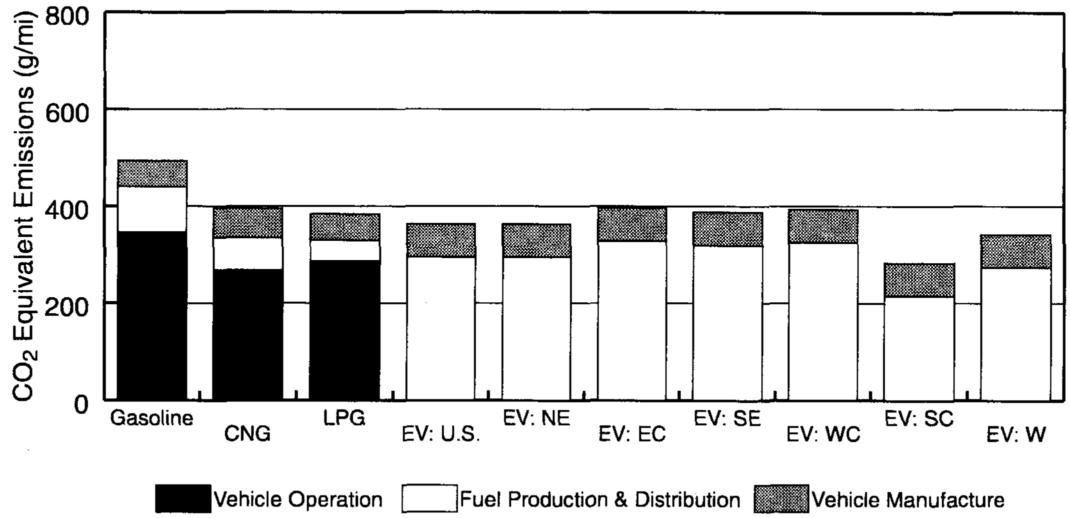
Source: Leiby et al., 1996, Table D-4

Figure 5.2 Fuel Cycle Greenhouse Gas Emissions for Heavy-Duty Vehicles



Source: Leiby et al., 1996, Table D-4

Figure 5.3 Projected Fuel Cycle Greenhouse Gas Emissions of Battery-Powered Electric Vehicles by Region in 2015



Source: Singh (1997)

The analyses in Chapters 6 and 7 indicate that there is considerable opportunity to reduce carbon emissions in the electric utility sector. A substantial shift towards lower-carbon electric generating facilities will increase the carbon-reducing benefits of electric vehicles. For example, large shifts away from coal and towards natural gas, especially with combined cycle technology, will tend to push the relatively high EV emissions in regions whose dominant fuel is now coal (Figure 5.3) down towards the lower emissions prevalent in areas with primarily gas-fired electricity (e.g. California).

The AEO97 reference case already projects large increases in the numbers of electric and natural gas vehicles on the road. Primarily as a result of zero emission vehicle (ZEV) regulations in California, AEO97 foresees annual sales of 75,000 battery electric cars and 150,000 battery electric light trucks in 2010. To this is added more than a quarter million hybrid electric vehicles. By 2010, the AEO97 reference case projects nearly 2 million battery-electric and over 2 million hybrid electric light-duty vehicles in operation. Given the recent relaxation of ZEV mandates in California, this projection now seems optimistic. The AEO97 reference case also projects compressed natural gas vehicle sales at 325,000 units in 2010 with a total on-road stock of 2.6 million light-duty vehicles. This is more than thirty times the 82,000 CNG vehicles estimated to be on the road today (EIA, 1996c, Table 1). We retain these alternative fuel vehicles in all three scenarios, but do not expand them.

Among the alternative transportation fuels under consideration, biomass fuels derived from wood appear to have the greatest potential to reduce greenhouse gas emissions. Whereas ethanol derived from corn may actually produce higher levels of CO_2 equivalent emissions than conventional gasoline (depending on the fuel used to power the distillation plant, and other factors), ethanol derived from cellulosic sources (wood, switchgrass, wood wastes, agricultural residues, municipal solid waste), can reduce carbon emissions by about 90% for both light-duty and heavy-duty vehicles (Figures 5.1 and 5.2). Cellulosic ethanol has the potential to be more effective than compressed synthetic natural gas derived from wood, partly because of the energy that must be used to compress methane for storage on board the vehicle, and partly because cellulosic ethanol production yields by-products that can be used to generate more electricity than is required to produce the ethanol (Delucchi, 1991, Table 9b; Wang, 1996).

Both battery electric vehicles and compressed natural gas vehicles, but especially battery-powered vehicles, are likely to cost more than conventional gasoline vehicles, will require more frequent refueling, and will have reduced range (Greene, 1994). It does not appear likely that most consumers will consider these drawbacks to be outweighed by the likely lower fuel costs for these vehicles. Thus, we expect these potential low CO_2 fuel technologies will not easily achieve the business-as-usual forecast market shares (of course, technological breakthroughs in batteries or gaseous fuel storage could make these vehicle technologies much more attractive). It is for these reasons that we focus below on the use of cellulosic ethanol as a transport fuel.

5.3 SCENARIOS FOR 2010

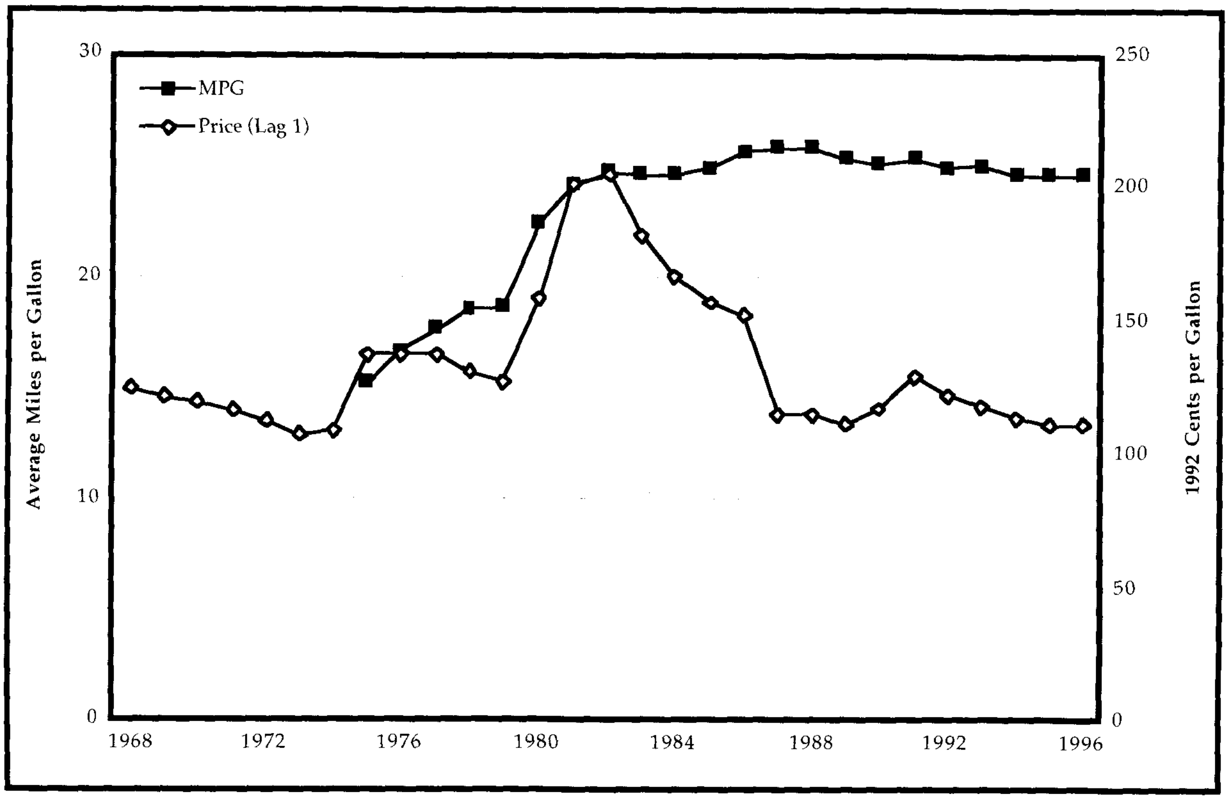
5.3.1 The Business-as-Usual Scenario for Transportation

The AEO97 reference case serves as the business-as-usual case, except for its forecast of increasing light-duty vehicle MPG through 2015. The EIA AEO97 reference case projects an increase in passenger car MPG from 27.5 in 1997 to 31.5 in 2010 and 32.6 in 2015. Light truck MPG is projected to increase from 20.5 to 22.9 MPG in 2010 and 24.2 MPG in 2015. We view this as inconsistent with the historical record, which appears to us to indicate that, without increasing fuel prices or a policy intervention such as fuel economy standards, MPG is not likely to increase. Thus, we incorporate zero MPG improvement after 1997 for light-duty vehicles into our business-as-usual case, reflecting the view that the current level of CAFE standards are and probably will remain a binding constraint on light-duty vehicle fuel economy throughout the business-as-usual forecast.

From 1982 to 1997, light-duty vehicle fuel economy remained essentially constant, as shown in Figure 5.4. Of course, motor fuel prices declined sharply at the beginning of the 1983-1997 period, but are at about the same levels today as they were in 1986, and as they were in the early 1970s prior to the first oil price shock. Given that the AEO97 oil price forecast projects no significant increase in oil or gasoline prices through 2015, it is reasonable to ask why fuel economy should increase. The EIA's view is that advances in motor vehicle technology will permit not only fuel economy but other vehicle attributes such as performance and weight to be increased at lower costs, resulting in greater consumer satisfaction. There is a very small increase in the price of gasoline through 2010, and this together with a slowing of income growth may allow the rate of technological advance to catch up with and pass the effect of consumer demand for larger, more powerful vehicles. Because a significant slate of cost-effective current and future fuel economy technologies are represented in the reference case input data, the model takes advantage of them even though fuel prices do not increase. NEMS would make greater use of the technologies if prices increased significantly, but the model is driven partly by technology availability and partly by changes in economic parameters. To some extent, the fuel economy benefits of these technologies are offset by a predicted increase in demand for performance. Nonetheless, a 5 MPG gain remains.

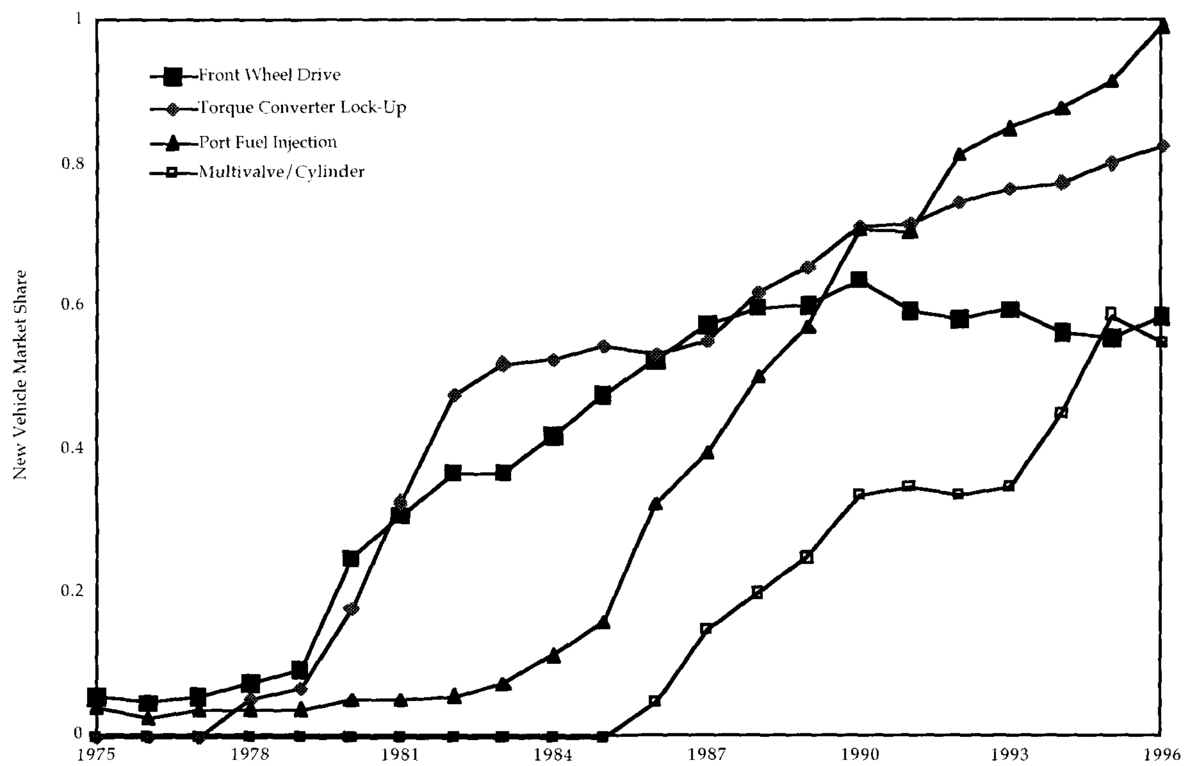
It is difficult to separate out analytically the impacts of CAFE standards and the effect of the marketplace in pushing fleet fuel economy one way or the other. However, we believe that the most likely explanation for the stagnation of fuel economy levels over the past decade is that the CAFE standards have tended to act as a floor on fuel economy, that without the standards the market level of fuel economy would have been lower than it was. We note that important fuel economy technologies, such as fuel injection, front-wheel drive, lock-up torque conversion, 4-valves per cylinder, overhead cam design, improved aerodynamics, and others, all increased their market penetration over the 1983-1997 period (Figure 5.5). Fuel economy technologies were adopted, yet average fuel economy did not increase. There are two major reasons. First, much of the potential to improve fuel economy was used instead to increase average light-duty vehicle horsepower by 55% and weight by 13% from 1983 to 1996 (Heavenrich and Hellman, 1996, Table 1). The second reason is that the impact of a technology on fuel economy depends on how that technology is implemented. To some extent, the fuel economy benefit of a technology is inherent in it. But to a degree, the benefit also depends on the details of vehicle design, specifically whether the technology is implemented with the purpose of increasing MPG or with some other purpose in mind.

Figure 5.4 New Light-Duty Vehicle Fuel Economy and Gasoline Prices, 1967-1996



If CAFE was in fact a binding constraint during the past decade and remains so today, fleet MPG will not begin to increase significantly until a market equilibrium is reached wherein actual fleet fuel economy becomes equal to the fuel economy level that would be achieved in the absence of CAFE standards. In our view, estimating "free market" fuel economy levels is basically a judgment call. We have assumed that market equilibrium will *not* be reached in the base case, so that fleet fuel economy will remain unchanged. In other words, we assume that, although fuel economy technology will continue to be adopted, it will be used to provide other benefits than fuel economy, particularly increased size and performance. Note that the AEO97 reference case also projects increased performance and size over the forecast period; the difference here is a matter of degree, not one of radically different visions of the most likely future.

Figure 5.5 Use of Fuel Economy Technology In New Light-Duty Vehicles



5.3.2 The Efficiency Scenario For Transportation

The efficiency case was created by making reasonable, incremental assumptions about how a concerted effort to accelerate the development and promote the adoption of low greenhouse gas technologies could reduce emissions by the U.S. transportation sector. In this section, the specific changes made to the business-as-usual case are described in detail.

5.3.2.1 Changes to the Modal Models

The efficiency scenario assumes that the time required for market introduction of advanced technologies can be reduced by 25% through increased emphasis on technology R&D, and that several new technologies will be developed that would otherwise not be available in significant numbers before 2010. For light-duty vehicles, these technologies include the following:

- A direct-injection stratified charge (DISC) gasoline engine,
- A turbocharged direct-injection clean diesel engine (TDI Diesel) that meets current and future emissions standards,
- Advanced drag reduction, materials substitution, and engine friction reduction (Drag VI),
- A gasoline/electric hybrid vehicle (Gasoline Hybrid), and
- A diesel/electric hybrid drive vehicle (Diesel Hybrid).

In fact, the diesel hybrid and the 2-stroke engine were not included in the efficiency scenario in order to reduce the number of new engine technologies introduced. We chose the gasoline over the diesel hybrid because its emissions of conventional pollutants can very likely be reduced to extremely low levels, making it attractive for air quality reasons. In the high-efficiency/low-carbon scenario, both the 2-stroke and the diesel hybrid are included (the 2-stroke is assumed to be applicable only in compact or smaller-sized vehicles). The result is that new powerplant technologies all but entirely replace today's conventional gasoline engine by 2015 in the high efficiency scenario. This seems a very ambitious undertaking and one that would require greater expense and a higher degree of technical success than is consistent with the efficiency scenario.

The efficiency scenario assumes a cost reduction of about one-third over estimates developed by OTA (1995) for the advanced technologies shown in Table 5.2, based on the potential for learning-based cost reductions discussed earlier. Among conventional technologies, the cost of CVTs was reduced from $250 to $150 and the cost of VVT was cut in half for passenger cars and left unchanged for light trucks. The cost reductions are intended to reflect the success of an enhanced R&D effort.

In the truck freight sector, several new technologies were brought into the forecast by reducing the fuel price threshold at which they would become attractive to buyers. These include:

- The LE-55 diesel engine with a 21% efficiency improvement for heavy trucks,
- Reduced empty weight,
- The turbo compound diesel engine, and
- Advanced drag reduction.

The low-emission, 55% thermal efficiency (LE-55) diesel engine is a research target of the U.S. Department of Energy's Office of Transportation Technologies. Compression ignition (diesel) engines are the most efficient heat engines currently available. Very large units (in stationary or marine applications) achieve thermal efficiencies (work output as a ratio to energy content of fuel) of 50%. The best turbocharged diesel engines for heavy trucks achieve 45% thermal efficiency, versus 24% for gasoline engines. The DOE's Office of Heavy Vehicle Technology has established a goal of 55% thermal efficiency for heavy truck engines as an intermediate target on the way to a long-term goal of 63%. These improvements are to be achieved through a combination of increased peak pressure, insulation of pistons, cylinder walls and heads to reduce heat loss, effective recovery of exhaust heat, friction reduction, and improved turbocharger efficiency (U.S. DOE/OHVT, 1996).

For commercial aircraft, an efficiency improvement of 40% was projected for 2015 for new aircraft, comprised of 25% engine efficiency gains and 15% aerodynamics and materials substitution. Also, load factors were assumed to increase to 70% in accord with industry projections as a result of advanced informational and operational technologies. Finally, railroad freight efficiency per ton-mile was assumed to improve at 2% per year, actually somewhat lower than the 2.8%/yr. rate experienced over the past 20 years.

5.3.2.2 New Technologies

Table 5.2 shows the fuel economy benefits, price impacts, years of introduction, effects on vehicle weight, and effects on vehicle performance of the five new technologies that were added to the AEO97 reference case set. Detailed assumptions underlying the cost of fuel economy improvement estimates shown in Table 5.2 are provided as an appendix to this chapter. In order to meet current and future emissions standards, the DISC and TDI Diesel engines, as well as the two-stroke engine included in the business-as-usual case, will require the development of practical, lean-combustion nitrogen oxide catalysts. Catalyst technology for treatment of exhaust emissions has been advanced significantly over the past few years and, with further research, the prospects for its early commercialization appear to be very good (e.g., Buchholz, 1997; Strehlau et al., 1997). Achieving equivalent results for diesel exhaust NO_X appears to be more difficult, and commercialization of diesel catalysts is likely to occur several years after introduction of gasoline-engine catalysts (U.S. Congress, OTA, 1995). In addition, the DI Diesel will require advances in fuel and emissions control technology in order to meet likely future particulate standards.

Fuel economy benefits, incremental costs and other changes are calculated with reference to a 1995 technology gasoline vehicle. In the NEMS model, light-duty vehicles are classified into passenger cars vs. light trucks, domestic vs. imported, with six size classes for each category. In each class, the 1995 base vehicle has the average characteristics of cars in its class. For example, half of the passenger cars in 1995 had 4-valve per cylinder engines, but less than 10% of the light trucks did (Heavenrich and Hellman, 1996). Thus, the 1995 base vehicle is credited with half of the fuel economy improvement potential and half of the increased cost of 4-valve technology. One hundred percent of passenger cars and 99% of light trucks had port fuel injection, and so the base year vehicles are given 100% and 99% of the fuel economy benefit and cost of fuel injection technology. Future fuel economy improvements are calculated based on the additional penetration of fuel economy technologies beyond the business-as-usual case. Thus, the ability of further use of port fuel injection to improve fuel economy is negligible, while considerable potential remains for 4-valve technology.

Table 5.2 New Light-Duty Vehicle Technologies Added to the Efficiency and High-Efficiency/Low-Carbon Scenarios[+]

Technology	MPG Benefit (%)* (EFF, HE/LC)	OTA Price Increase	Scenario Price	Introduction Date* (EFF, HE/LC)
DISC	18, 23	$450	$300	2000, 2000
Turbo DI Diesel	40, 40	$1100	$750	2004, 2004
Hybrid/Gasoline	33, 42	$3000	$2000	2005, 2005
Hybrid/Diesel	54, 72	$3500	$2300	2005, 2005
Drag VI	12, 12	$256	$256	2012, 2012
Gasoline Fuel Cell	–, 84	–	$800	–, 2007

[+] For an explanation of the assumptions underlying these estimates please see the appendix to this chapter.

5.3.2.3 Valuing Energy Savings

The NEMS model values the fuel economy savings of advanced technology by computing the expected discounted value of annual fuel savings over a payback period. We used a 7% real discount rate over five years whereas the reference case assumes an 8% real discount rate over a four-year payback period. The issue of discounting fuel savings is discussed in greater detail in Section 5.3.5.

5.3.2.4 Trends in Vehicle Performance

The NEMS model predicts consumer demand for increased performance and then adjusts new car MPG downward to reflect the effect of higher horsepower on fuel economy. The model's predictions are consistent with recent trends in light-duty vehicle performance since the early 1980s. Over this period, new vehicle fuel economy was constrained by the federal Automotive Fuel Economy Standards (CAFE) to levels higher than the market would otherwise have demanded. Gasoline prices fell precipitously, starting in 1983 and reaching pre-1974 levels by 1987 (Figure 5.4). As a result, new technology adopted since the mid-1980s, that could have increased fuel economy, was instead used to hold fuel economy constant while increasing vehicle horsepower and weight. The ratio of horsepower to weight for passenger cars increased by 50% from 1982 to 1996). The NEMS horsepower equations essentially continue this trend of ever-increasing performance.

Continued use of new technology to increase performance without increasing fuel economy is consistent with the continued low motor fuel prices projected in the AEO97 reference case. The reference case foresees gasoline prices rising from $1.15 in 1995 to $1.23 in 2010 and falling to $1.18 per gallon in 2015 (1995$). Such variations are within the noise of year-to-year fluctuations. For example, the actual average price of gasoline in 1995 was $1.20 and the average price for 1996 will likely exceed $1.30 per gallon (EIA, 1997, Table 9.4). With no increase in price and binding fuel economy standards, it is likely that performance and weight will continue to increase and fuel economy will not.

In the efficiency case, the trend toward ever greater horsepower is questionable. In the presence of higher fuel economy standards, voluntary commitments by manufacturers to meet GHG targets, "greener" consumers, externality-based fuel taxes, or some other change in policies or preferences focusing consumers' and manufacturers' attention on efficiency, it is likely that performance trends would change. Nonetheless, we retain the NEMS performance projection in the efficiency case, but relax it in the high-efficiency/low-carbon case by permitting only half of the projected increase in horsepower. This results in new vehicle fuel economy levels 1-2 MPG higher in the high-efficiency/low-carbon case than would otherwise be the case.

5.3.2.5 NEMS New Light-Duty Vehicle Fuel Economy Estimates

Transforming the technology of transportation energy use takes time. First, manufacturers must implement a new technology. New designs must be engineered, tested, and certified to meet government standards. Generally, capital equipment will also have to be replaced or retooled. The orderly replacement of long-lived production facilities (engine production lines may last 15 years, or more) is important to holding down the cost of technological change. Second, consumers must become accustomed to the new technology, and the supporting infrastructure of maintenance and repair must be developed. Finally, new technologies must compete with existing technologies and with other new technologies. In general, a single technology will not dominate all possible applications (vehicle types and consumer preferences). For all these reasons, new technologies rarely achieve 100% (or even 10%) market penetration of the new vehicle fleet in the first year of introduction. The NEMS model simulates the gradual evolution of technology market shares toward their eventual equilibrium levels by means of technology adoption curves calibrated to historical rates of adoption.

As a result, the NEMS forecast of average fuel economy for new vehicles will lag behind the full technological potential. This is illustrated in Table 5.3, which lists all of the best technology predicted to be available in 2010 and 2015 in the efficiency scenario, except that the diesel rather than the gasoline hybrid is included. The effects of regulations that are likely to reduce fuel economy are also included, but further increases in performance (horsepower/weight) predicted by the NEMS model are not, i.e., horsepower-to-weight ratios are assumed to remain constant at 1997 levels. (This applies only to Table 5.3 – all scenarios incorporate substantial increases in hp/wt ratios.) The combined effect of all technologies could improve the fuel economy of the average passenger car by 100% to 55 MPG in 2010, and by another 20% to over 60 MPG in 2015. Yet, even in the high-efficiency/low-carbon scenario, these levels are not achieved by the new car fleet in the NEMS forecasts.

Table 5.3 Maximum Technological Fuel Economy Potential Versus NEMS New Car Average Estimates

Technology	2010 Fuel Economy Improvement (%)	2015 Fuel Economy Improvement (%)
Material Substitution IV	9.9	13.2
Drag Reduction V	9.2	12.0
Engine Friction III	5.0	6.5
Tires III	5.0	7.0
ACC II	1.0	1.0
Electric Transmission II	1.5	1.5
Electric Power Steering	1.5	1.5
Air Bags	-1.0	-1.0
Emissions Tier II	-1.0	-1.0
ABS	-0.5	-0.5
Side-Impact	-0.5	-0.5
Roof Crush	-0.3	-0.3
Diesel Hybrid	54.0	60.0
Total % Improvement*	100.0	123.0

1997 MPG 27.5	2010 MPG	2015 MPG
Maximum Use of All Fuel Economy Technology		
Miles per Gallon	55.0	61.3
Percent Improvement	100	123
New Car Salesweighted Average Fuel Economy: Low CO2 Scenario		
Miles per Gallon	37.5	41.4
Percent Improvement	36	51
New Car Salesweighted Average Fuel Economy: Breakthrough Scenario		
Miles per Gallon	43.1	50.2
Percent Improvement	57	83

* Total percent improvement is computed as $[(1 * \frac{54}{100})(1 + \frac{30}{100}) - 1] * 100$. Summing rather than multiplying the smaller percentage improvements yields a more conservative estimate.

Clearly, faster rates of fuel economy improvement than predicted in either scenario are achievable, but at added cost. The constraint that fuel economy improvements be approximately cost-effective requires that the changeover of technologies and manufacturing capital occur at approximately normal rates. This causes realized new car MPG levels to lag considerably behind the full technological potential. On the one hand, this implies that considerable additional energy-efficiency improvement can be made beyond 2015. On the other, it implies that markets must be encouraged, through public policy measures, to make continuous improvements if cost-effective reductions in CO_2 emissions are to be realized.

5.3.2.6 Changes to the Heavy Truck Model

In contrast to the business-as-usual case, the efficiency scenario for heavy trucks:

- Advances introduction dates for two fuel economy technologies,
- Introduces one additional technology,
- Expands the applicability of several truck technologies,
- Reduces the "trigger price" at which the technologies are assumed to become cost-effective, and
- Accelerates the rate at which new technologies are assumed to penetrate the new truck market.

The AEO97 reference case assumes that the Turbocompound Diesel Engine and the Advanced LE-55 Heat Engine will not be available through 2015. The efficiency scenario assumes these technologies will be introduced in 2003. Advanced drag reduction, which is also excluded from the reference case for heavy trucks is assumed to have become available in 1997.

The additional technology introduced is reduction in vehicle empty weight through material substitution. Reducing vehicle empty weight by 10% should be possible, with a consequent 3% increase in fuel economy (Roberts and Greene, 1983; Greene, 1996a, Table 5.5). Reduced empty weight is assumed to be applicable to all types of heavy trucks.

The AEO97 reference case assumes that advanced drag reduction, the turbocompound diesel, and the LE-55 heat engine will be applicable only to the heaviest diesel trucks. The efficiency case extends the applicability of these technologies to medium-heavy diesel trucks, as well. However, the fuel economy benefits of advanced drag reduction are cut from 18% to 10% for medium trucks to reflect the fact that they are generally operated at lower speeds.

A key factor governing the use of fuel economy technology in the NEMS Heavy Truck Model is the "trigger price." Until market fuel prices reach the "trigger price" level specified for a technology, the technology will not be introduced. Diesel fuel prices never exceed $8.70 (1995$) per million Btu ($1.21/gal.) in the AEO97 reference case. Trigger prices for all but existing technologies, however, are $9/MMBtu, or greater in the reference case. The efficiency case assumes that all of the new technology can be made cost-effective at $8/MMBtu.[9]

Other parameters controlling the rate and extent of market penetration for technologies were also changed. One of these is the number of years until 99% of the maximum potential market penetration is achieved. For improved tires and lubricants, electronic engine controls, and electronic transmission controls, a value of 20 years is assumed in the AEO97 reference case. But for advanced drag reduction, turbocompound diesel, and the LE-55 engine, 99 years is the assumed value. For the efficiency case, all were set at 20 years. The AEO97 reference case assumed that the LE-55 engine would have a maximum market potential of 50% for heavy-duty diesels. The efficiency scenario assumes a 100% maximum for heavy diesels, but only 50% for heavy gasoline, LPG, and CNG trucks. Likewise, the maximum market potential for other advanced technologies was increased to 100% for the heavy diesel market, but left at the reference case values for other fuel types. For medium diesel trucks the maximum penetration for new technologies was raised to 90%, but left at the reference case levels for other fuel types. These changes do not imply that any of these technologies will actually reach maximum market penetration over the forecast time period. Table 5.4 summarizes the primary fuel economy technologies for heavy trucks in the efficiency scenario for 2010.

Table 5.4 Key Heavy Truck Fuel Economy Technologies for the Efficiency Scenario in 2010

Technology	Year of Introduction	Trigger Price (1995$/MMBtu)	Maximum Market Potential (other / diesel)	Fuel Economy Improvement % (medium/heavy)
Improved Tires & Lubes	1994	$7.75	80% / 100%	10% / 6%
Electronic Engine Controls	1994	$7.75	70% / 100%	2%
Elec. Transmission Controls	1994	$7.75	75% / 100%	5% / 2%
Advanced Drag Reduction	2000	$7.75	25% / 100%	7% / 18%
Turbocompound Diesel	2000	$7.75	25% / 100%	15% / 17%
LE-55 Heat Engine	2003	$7.75	50% / 100%	19% / 21%
Reduced Empty Weight	1997	$7.75	90% / 100%	3%

5.3.2.7 Changes to the Rail Model

The AEO97 reference case scenario assumes an annual rate of reduction in rail freight energy use per ton-mile of 1%. Since 1972, the average annual rate of reduction in energy use per ton-mile has been 2.8% per year. The vast majority of this improvement has been due to operational efficiency improvements reflected in increased load factors per car (Greene and Fan, 1995, p. 15). Higher load factors are partly due to the restructuring of the rail industry following deregulation in 1980, and partly due to the use of advanced technology for managing operations. Technologies such as lighter weight and higher capacity cars, lower resistance axle bearings, rail-wheel lubrication and improved efficiency locomotives also played an important role (Cataldi, 1995). These technologies are, as yet, still only partially implemented. Based on Cataldi (1995), advanced technologies that can play a role in substantially reducing rail energy use in the future include the following:

- **Flywheels:** Trains presently give up large amounts of kinetic energy on downgrades that could be transferred to flywheels and later used to power the train. The volume and mass necessary to store huge quantities of power can be readily accommodated on trains.

- **Oxygen-enrichment to increase engine thermal efficiency:** Membranes that exclude part of the free nitrogen in the air, thereby enriching the oxygen concentration, can be incorporated into locomotives' air filtration systems. This technology should benefit new, higher power density engine designs, while helping to hold down their nitrogen oxide emissions.

- **Alternative fuels:** Railroads and locomotive manufacturers have been studying and testing the use of natural gas fired locomotives. Once again, the ability of trains to accommodate the volume and mass of storage systems for liquefied natural gas gives them a distinct advantage over smaller vehicles in the application of this technology. Although natural gas locomotives are not expected to provide energy-efficiency gains over diesels, natural gas will produce fewer CO_2 and NO_X emissions and reduce U.S. dependence on oil.

- **Fuel cells:** Beyond 2010, fuel cells for locomotives hold promise. Locomotives already use electric drive systems. And carrying fuel, even compressed hydrogen in large volumes, is less of a problem for trains than for highway vehicles.

Because existing energy-efficiency technologies have yet to achieve full utilization, because other promising options exist, and because further operational efficiency gains are likely with the advance of information technology and some additional railroad consolidation, rail energy-efficiency improvements could continue at a substantial rate. A concerted effort to develop and implement cost-effective technologies is represented here by a 2% annual improvement in ton-mile efficiency in the efficiency case compared with the 1% rate assumed in the AEO97 reference case.

5.3.2.8 Changes to the Air Model

No new technologies were introduced in the NEMS Air Travel Model, but several important changes were made to promote and accelerate the introduction of fuel efficient technology in accordance with goals set by the Committee on Aeronautical Technologies, Aeronautics and Space Engineering Board of the NRC. Broadly, these goals call for a reduction in fuel burn per seat of about 40% by the 2010 to 2015 time period, to be achieved through a combination of improved propulsion system performance (25%) and aerodynamic and weight improvements (15%) (NRC, 1992, p. 49).

Once again, in the AEO97 reference case, new technologies do not enter the commercial aircraft market because trigger prices are set well in excess of $1.00 per gallon and jet fuel prices never exceed $0.80/gal. over the forecast period. Trigger prices for ultra-high bypass turbo-fans, already in use on the new Boeing 777s, were lowered to $0.58/gal., just slightly above current jet fuel prices. Advanced aerodynamics, weight reduction through advanced materials use, and improved engine thermodynamics, were all given the same, lower trigger price. The prices of turboprop engines and laminar flow control were left at levels high enough to prohibit their introduction on new aircraft through 2015.

Ultra-high bypass turbofans were introduced in 1995. The other three technologies were assumed to be introduced in 2000. Consistent with estimates presented in NRC (1992), Greene (1992, Table 4), and Greene (1996b), the efficiency improvement potentials for all four new technologies were set at 15%.

Finally, the AEO97 reference case predicts no changes in aircraft load factors. Aircraft industry analyses foresee commercial load factors increasing to 70% by 2015 (Boeing, 1995, p. 25; McDonnell Douglas, 1996, p. 18). The industry view is adopted in the efficiency scenario, on the grounds that it will very likely be advances in information technology that permit the increase in load factors. On the other hand, although the industry predicts an increase in aircraft size (seats/aircraft) of about 15% by 2015 while the AEO97 reference case does not, no such increase is included in the efficiency scenario on the grounds that more seats per aircraft will be less a reflection of technological change than of airframe choice.

5.3.2.9 Introduction of Cellulosic Ethanol

Alternative fuels derived from fossil fuels have limited potential to reduce greenhouse gas emissions. The full fuel cycle greenhouse gas emissions of fossil fuels have been compared in detail by Delucchi (1991, Table 9a), Wang (1996), U.S. DOE (Leiby et al., 1996, Tables D-4 and D-5), and others; see Wang (1996) for a review. Several fuel alternatives have lower CO_2 emissions than conventional or reformulated gasoline (RFG), most notably liquefied petroleum gases (LPG), methane and battery-powered electric vehicles in certain regions, whether compressed (CNG) or liquefied (LNG). Estimates of greenhouse gas emissions are strongly dependent on context and assumptions. Absolute levels and sometimes the relative rankings of fuels vary across studies. Several general patterns seem to hold up, however. For example, fossil-fuel based alternatives to gasoline or diesel fuel, including battery-electric vehicles where substantial amounts of coal are used for electricity generation, offer about a 20% net reduction in greenhouse gas emissions per mile (Figure 5.3).

In the context of this analysis, a 20% reduction in greenhouse gas emissions will not create a strong incentive to adopt an alternative fuel. For light-duty vehicles, if society's willingness to pay for greenhouse gas emissions reductions were on the order of $25-$50 per tonne of carbon, this could justify up to a $0.06 to $0.12 per gallon subsidy[10] for a fuel that produced no greenhouse gas emissions. A 20% reduction would therefore be worth $0.01 to $0.02 per gallon, hardly enough to get motorists' attention. Also, the principal near-term alternative fuels entail some increase in vehicle cost or loss of amenity (Leiby et al., 1996). Thus, unless much higher incentives are introduced, it is unlikely that enough substitution of alternative fossil fuels for conventional gasoline will occur to produce significant greenhouse gas reductions in transportation (Leiby et al., 1996).

Alternative fuels produced from renewable biomass feed stocks can yield significant reductions in greenhouse gas emissions. The most recent estimates indicate that ethanol derived from cellulosic feed stocks (as opposed to grain) produces less than 1% as much greenhouse gas emissions on a fuel cycle basis as conventional gasoline or diesel fuels (Singh, 1997).[11] Table 5.5 shows the greenhouse gas emission coefficients used to estimate the effects of cellulosic ethanol use and increased demand for diesel fuel on transportation sector greenhouse gas emissions. Ethanol from cellulose generates negligible amounts of greenhouse gases in comparison to fossil fuels or ethanol from grain. Whether ethanol is derived from grain or woody biomass, the carbon in the fuel itself does not count because equivalent carbon will be recaptured from the atmosphere by the next rotation of crops. The differences lie in feed stock cultivation, fertilizer manufacture, and fuel production. Corn requires more cultivation and more fertilizer than woody crops, and fertilizer production, in particular, generates significant greenhouse gas emissions. Whereas distillation of alcohol after the fermentation of grain is energy intensive, by-products from the wood-to-alcohol process will produce excess power, on net, resulting in a greenhouse gas credit for replacing fossil fuels with biomass in the generation of electricity. Indeed, given current practice, ethanol from corn may produce more greenhouse gas emissions than gasoline, on a per Btu basis. Thus, ethanol from cellulosic feed stocks will not only reduce greenhouse gas emissions by replacing gasoline, but might achieve even greater benefits by replacing ethanol from corn. However, the net greenhouse gas balance of ethanol production from corn is strongly dependent on future corn yields, the market for distillation byproducts, and the efficiency of and fuel used in distillation (currently, coal is often the preferred fuel because of corn-based ethanol's disadvantage in greenhouse gas emissions, but future widespread use of corn stillage as fuel would swing ethanol's greenhouse gas emissions strongly towards a positive balance).

A new process for producing ethanol from cellulosic biomass that appears to have the potential to dramatically reduce costs is under development by the U.S. DOE's National Renewable Energy Laboratory (Chem Systems, Inc., 1993). After initial preparation of the biomass, pretreatment with sulfuric acid and then steam is used to expose the cellulose and convert xylan to xylose. Two percent of the resulting mixture is separated for conversion to cellulase, an enzyme that hydrolyzes cellulose. The cellulase is then combined with the rest of the mixture fermented in a key step known as simultaneous saccharification and fermentation (SSF) because the hydrolyzation of cellulose and the fermentation of xylose occur simultaneously. The inclusion of xylose fermentation in this step increases the output of ethanol by about 25% over previous processes. Effluent from the SSF process goes to an ethanol purification and solids separation phase, which produces ethanol and solids. After removal of water, the solids are burned as fuel to cogenerate steam and electricity required for the plant, with surplus electricity that can be sold as a byproduct.

Table 5.5 Greenhouse Gas Emissions Factors for Transportation Fuels

Fuel	g/Btu	Btu/gallon	g/gallon
Conventional Gasoline			
Summer	0.10554	114,500	12,084
Winter	0.10304	112,700	11,613
Average	0.10421	113,537	11,832
Diesel	0.09617	128,700	12,377
Ethanol from corn	0.13390	76,100	10,190
Ethanol from cellulose	0.00076	76,100	58

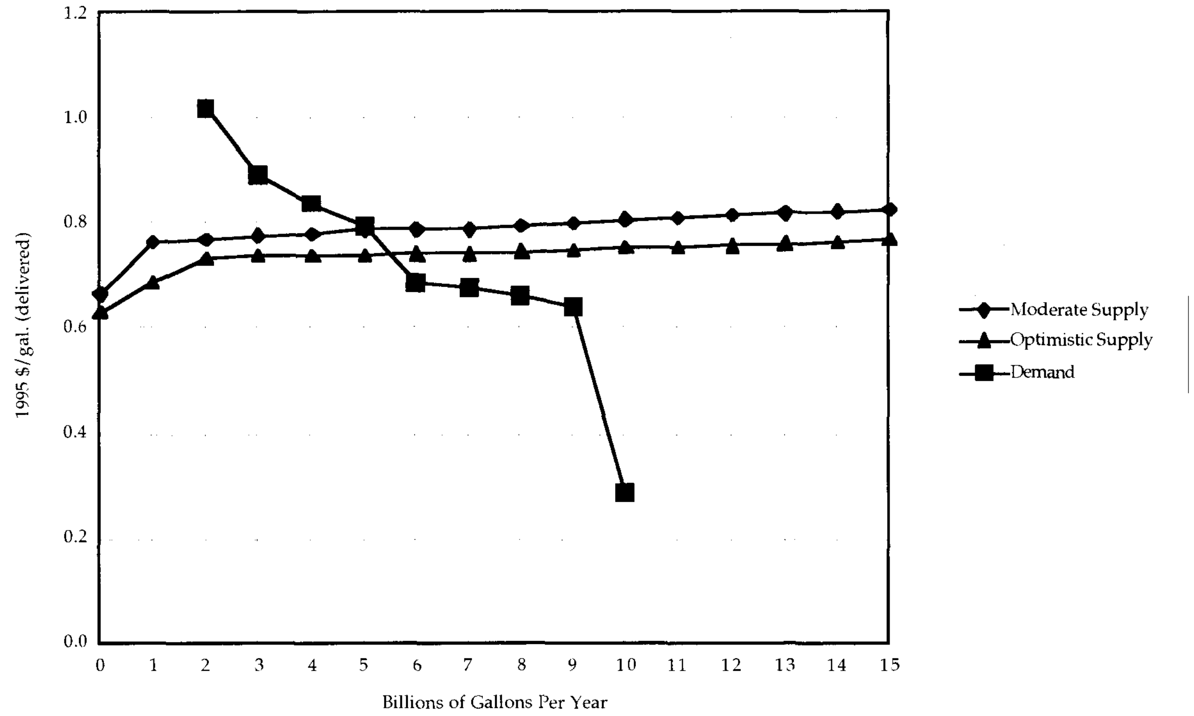
Source: Singh (1997)

Initial estimates of the cost of ethanol produced by the NREL process ranged from $0.78 to $1.27 (1990$) per gallon, plant gate price (Chem Systems, 1993, Tables II-9 to II-13). However, recent cost projections (Bowman et al., 1997) based on a comprehensive assessment of feed stock supply in the United States (Walsh et al., 1997) and anticipated improvements in the ethanol conversion process predict that much lower production costs can be achieved by 2010 or 2015. Ethanol can be produced from a variety of cellulosic feed stocks: short rotation woody crops, switch grass, softwood and hardwood wastes, agricultural residues, and even municipal solid wastes. Selecting the lowest cost feedstock at each level of output, aggregate ethanol supply curves were constructed for 2000, 2005, 2010, and 2015 under "moderate" and "optimistic" assumptions. The optimistic curves assume that the yield improvements of the moderate case are accelerated by five years, with the net result that the real cost of feed stocks does not rise over time. The moderate scenario curves are used in the efficiency scenario. The optimistic case, being similar in intent to our high-efficiency/low-carbon scenario, is used in that scenario.

In the moderate scenario, ethanol production costs drop dramatically after 2005, the year in which advanced ethanol conversion technology is assumed to be introduced. In 2000, the first billion gallons cost $1.10 (1995$) per gallon at the plant gate, which rises to almost $1.25 per gallon at a 10 billion gallon output level. These prices exclude motor fuel taxes and transportation costs. By comparison, the average refinery price of all grades of gasoline in 1995 was $0.63 per gallon (EIA, 1996a, Tables 5.20 and 5.21). Because ethanol has only about two-thirds of the energy content of gasoline, the comparable price of ethanol per gasoline energy equivalent gallon would be $1.63 for the first billion gallons and $1.85 at the 10 billion gallon level of output. By 2010, the cost of ethanol drops to about $0.75 per gallon ($1.11 per gasoline equivalent gallon) at the 1 billion gallon output level, $0.79/gallon ($1.17 equivalent) at 10 billion gallons of production. Even in the optimistic case, the first billion gallons cost $0.67/gallon ($.99 equivalent), increasing to $0.73/gallon ($1.08 equivalent) at the 10 billion gallon output level. Despite dramatic reductions in the cost of producing ethanol from biomass, because of the lower energy content of ethanol, ethanol still cannot compete with gasoline as a pure fuel.

We conclude that the market for cellulosic ethanol in 2010 will be largely as a blending component for gasoline. Demand curves for ethanol for blending with gasoline have been estimated by Hadder (1997) for the year 2010. These show the value to refiners of being able to produce a gasoline refined to be blended with alcohol downstream. Ethanol increases the gasoline's octane rating and adds oxygenates that are required in certain areas under the Clean Air Act. The demand for ethanol as a blending component turns out to be sensitive to the market share of RFG. The more RFG that is required, the lower the demand for ethanol. We assume that RFG's market share remains at its current level of about 30%. Estimated ethanol demand increases as its price declines, from 2 billion gallons per year at an ethanol price of just over $1 per gallon to 5 billion gallons at $0.80/gallon and 9 billion at $0.65/gallon. From this point, increases in demand associated with further price decreases drop off sharply as the limits of economical blending are reached. The moderate 2010 supply curve for cellulosic ethanol intersects the demand curve at about 5 billion gallons per year (Figure 5.6).

Figure 5.6 Biomass Ethanol Supply and Demand for Ethanol in Gasoline Blending



These calculations include no tax subsidy for cellulosic ethanol from biomass. If the projected supply curves are correct, cellulosic ethanol would require no subsidy to be economically attractive as a blending component for gasoline. The current tax subsidy for ethanol – now produced from grain – is due to expire, and the future of the industry is uncertain. Assuming discontinuation of the subsidy, cellulosic ethanol would displace corn-based ethanol from the gasohol, yielding significant greenhouse gas emissions reductions.

5.3.2.10 Adjustment of NEMS Gasoline Forecast

The 5.5 billion gallons of cellulosic ethanol demanded in the efficiency case reduce greenhouse gas emissions by 13 million tonnes of carbon equivalent in 2010 compared to the business-as-usual case. Cellulosic ethanol is assumed to replace first corn-based ethanol, and then conventional gasoline. The Federal Highway Administration (FHWA) estimates that 1.214 billion gallons of ethanol were used in gasohol in 1995 (U.S. DOT/FHWA, 1996, Table MF-33E). If gasohol made from corn-based ethanol were to maintain a constant share of the gasoline market, then corn-based ethanol use would grow to 1,263 million gallons in 2010, then shrink to 1,119 million gallons in 2015. Table 5.6 shows the projected demand for cellulosic ethanol, the corn-based ethanol assumed to be replaced and the impact on fuel cycle greenhouse gas emissions. Because the upstream effects cannot be assumed to be accounted for in the other sectoral models, they are included here. Note that the reduction is shown in tonnes of carbon, while the emissions before and after are in tonnes of CO_2.

Table 5.6 Impact of Cellulosic Ethanol on Greenhouse Gas Emissions from Light-Duty Vehicles in 2010

	Efficiency	Optimistic
Cellulosic Ethanol (million gallons)	5,514	7,480
Corn Ethanol Displaced (million gallons)	1,263	1,119
Gasoline Equivalent Energy Displaced (million gallons)	3,696	5,014
GHG Emissions Before (million tonnes CO_2 per year)	46.6	62.2
GHG Emissions After (million tonnes CO_2 per year)	0.3	0.4
GHG Emissions Reduction (million tonnes C per year)	12.6	16.8

5.3.2.11 Adjustments for Increased Light-Duty Vehicle Diesel Use

Because the TDI Diesel engine and the Diesel-hybrid technologies were introduced in the NEMS Transportation Sector Model as fuel economy technologies, the fuel-type accounting algorithms of NEMS were bypassed. We introduced the advanced diesel in this way because we believe that its characteristics will be more similar to gasoline engines than the diesels available in the past. The TDI will fully meet all gasoline vehicle standards and will be quite similar in terms of performance, noise, and odor.[12] Thus, an adjustment must be made *ex post*, to transfer an appropriate amount of energy from the gasoline to the distillate category. The adjustment affects the energy use projections in three (relatively minor) ways. First, the TDI Diesel's impact is specified in terms of a change in miles per gallon. Since diesel fuel contains more Btu per gallon than gasoline and since the NEMS model assumes that gasoline is being consumed, the energy use transferred from gasoline to diesel must be increased by the ratio of diesel to gasoline Btus per gallon. Second, distillate fuel produces slightly less carbon emissions per Btu than gasoline. Therefore the estimated carbon emissions must be adjusted both for the slight increase in energy use and the slightly lower emissions per Btu for that greater energy use (the net result is a very small increase in carbon emissions). Third, and finally, the reduction in gasoline use reduces the potential pool for ethanol blending in gasoline. As a result, the demand for ethanol must be adjusted downward to reflect the lower level of gasoline use. The net result of all of these changes on energy use and carbon emissions is less than 1%.

5.3.3 The High-Efficiency/Low-Carbon Scenario for Transportation

The high-efficiency/low-carbon scenario postulates the introduction before 2010 of several new technologies and combines them with other changes to reflect greater success in developing and implementing low greenhouse gas technologies and greater public concern over greenhouse gas emissions. Note that successfully achieving these outcomes requires some technological breakthroughs, implying that the outcomes are significantly less certain than those in the efficiency case. As we pointed out in the introduction to this chapter, the high-efficiency/low-carbon scenario is best characterized as an "optimistic" version of the efficiency scenario's "most likely" assumptions. Both must be considered responses to intensified R&D efforst and new policy measures to push the market toward low-carbon technologies. A $50/ton carbon tradable permit price could be one of the necessary policies, but it is not the principal difference between our efficiency and high-efficiency scenarios.

5.3.3.1 Light-Duty Vehicles

Changes for light-duty vehicles include introducing a fuel-cell hybrid in the year 2007 and reintroducing the diesel hybrid and the 2-stroke engine for smaller vehicles. In the projections shown here, we assume that the fuel cell hybrid vehicle uses gasoline which is reformed to provide hydrogen for the fuel cell's operation (e.g., Jost, 1997). The vehicle could just as easily have been designed to operate on alcohol fuels. The gasoline fuel cell hybrid achieves an 84% efficiency gain over a conventional gasoline vehicle, assuming major progress not only in fuel cell and gasoline processor technology, but also in electric motors and other electric drivetrain components. Because a major breakthrough would be required to make this vehicle marketable, we do not attempt to estimate its cost. Instead, we assume that it will be cost-effective on a life-cycle cost basis – that is, that its incremental cost will be equal to its lifetime fuel savings. This implies a price increment of $800. Note that this value is not meant to be interpreted as a forecast of likely future fuel cell costs; instead it allows us to evaluate the consequences of such an optimistic outcome.

Some of the technologies necessary to produce an 84% efficiency gain for the fuel cell hybrid would also make the internal combustion engine hybrids, both gasoline and diesel, somewhat more efficient (e.g., ultra high-efficiency electric motors, improved energy storage devices with high specific power and high in/out efficiency). Fuel economy gains for the gasoline and diesel hybrids are boosted to 42% and 72%, respectively. A more optimistic assumption is made for the DISC engine, as well. Its fuel economy benefit is increased to 23% from 18%.

If Intelligent Transportation Systems technologies are highly successful, they should be able to improve traffic flow, resulting in higher on-road fuel economy. To reflect this, the on-road fuel economy factor, which otherwise deteriorates by 3% from 1997 to 2015, is held constant. The high-efficiency/low-carbon case further assumes that the current emphasis on horsepower (HP) will abate substantially, although increased HP will still be valued. This case is consistent with a change in attitudes favoring "greener" automobiles or policies to encourage higher MPG. To reflect greater public concern over greenhouse gas emissions, the demand for increased horsepower is reduced by decreasing its sensitivity to income, from an elasticity of 0.9 to 0.5.

As noted earlier, there are other potential technology breakthroughs capable of significantly reducing greenhouse emissions (e.g. breakthroughs in batteries for electric vehicles, or in gas storage for natural gas vehicles (see box)). These were left out of the high-efficiency/low-carbon scenario not because they are necessarily less plausible than fuel cells, but because the inclusion of large numbers of technology breakthroughs in a single scenario would be implausible.

Other Potential Breakthrough Technologies

Aside from the new technologies postulated in the high-efficiency/low-carbon scenario, other potential technologies could yield substantial reductions in greenhouse gas emissions with technology breakthroughs or, in some cases, with a substantial market push. In the light-duty vehicle market, for example, battery electric vehicles have potential to reduce greenhouse gases if they can greatly increase their market share and improve their energy efficiency. For example, several recent studies have concluded that, under plausible assumptions about EV efficiency and the mix of fuels and technology used to generate recharge electricity, use of EVs will yield net reductions of greenhouse gases. Delucchi (1997) estimates a national average reduction of 26% in 2015, with power generation heavily weighted to coal; whereas Wang (1997) estimates a 19% reduction in 2005. Areas with predominately natural gas-generated electricity could have much larger savings. Note, however, that these results are dominated by assumptions about EV and baseline gasoline vehicle efficiency, type of fuel and technology used for power generation, inclusion or exclusion of non-CO_2 greenhouse gases, and the types of trips replaced by EV use; it is relatively easy to construct plausible scenarios with much higher or lower reductions in greenhouse gases, or even increases (with coal-fired electric power and extremely efficient competing gasoline vehicles).

Crucial technological roadblocks for EV market penetration are:

- Battery improvements – especially higher specific energy and power, lower cost, improved longevity, higher in/out efficiency,
- Power electronics – especially lower cost, and
- Electric motors – especially higher efficiency over a range of driving cycles and higher specific power.

There are claims that transportation use of alternative fuels other than electricity (particularly compressed natural gas) will yield strong greenhouse benefits. In natural gas's case, recent analyses have shown contrasting greenhouse effects. For example, Delucchi (1997) estimates a 20% reduction in greenhouse gases compared to gasoline use in 2015, whereas Wang (1997) estimates a 5% *increase* in 2005. The primary difference in the two analyses is that Wang computes a 10% energy-efficiency penalty associated with switching to CNG, based on recent test data; Delucchi estimates an 11% improvement in energy efficiency based on potential efficiency gains from higher compression CNG engines. Delucchi's optimism may well be the more appropriate approach for the longer term, but at best CNG offers only a modest greenhouse emissions improvement.

Although we selected fuel cell vehicles fueled by gasoline (with onboard fuel processors) as the "breakthrough" technology in the high-efficiency/low-carbon scenario, some analysts believe that the direct use of hydrogen as a fuel is sufficiently more attractive to outweigh the disadvantages of hydrogen's low energy density (complicating onboard storage) and lack of a supply infrastructure (Ogden, 1977). The advantages of direct hydrogen include avoidance of the added weight and cost of the fuel processor and larger fuel cell required (fuel cell performance is reduced because the processor does not produce pure hydrogen), and reduced vehicle efficiency because of the energy losses in the processor and added vehicle weight (assuming the higher fuel storage weight for hydrogen is less than the weight savings from removing the processor and reducing fuel cell size). Although lack of infrastructure still represents a barrier, there have been advances in small scale-steam reforming of natural gas that could greatly ease the introduction of a viable hydrogen supply infrastructure (Ogden, 1977).

5.3.3.2 Changes to the Medium and Heavy Truck Model

Medium heavy trucks are typically operated locally in pick-up and delivery mode. For such vehicles, hybrid technology, with regenerative braking and energy storage capabilities, should offer significant advantages. It is assumed that a diesel hybrid becomes available to heavy trucks starting in the year 2005. This technology is assumed to offer the same 72% fuel economy benefit as the light-duty vehicle version.

Greater success in materials, aerodynamics, tires, and engines, should make these technologies more economically attractive to truckers. Since the NEMS Heavy Truck Model does not explicitly include an economic trade-off between fuel savings and technology penetration, this effect was simulated by shortening the time to 99% penetration for each technology by 30%. For most technologies, this implies a 15 year period from time of introduction to nearly full market penetration.

5.3.3.3 Changes to Other Modes

Several changes were made to the commercial air model inputs. Starting in 2005, propfans were assumed to be available for smaller commercial aircraft. Propfans offer a 20-30% efficiency improvement over high bypass turbofan engines, and 10-15% over even ultra-high bypass engines. Development of propfans has been hindered by concerns about initial cost, maintenance, and vibration. Propfans are made available to only one-third of new aircraft in the high-efficiency/low-carbon scenario. Additionally, partial success in hybrid laminar flow (HLF) technology to reduce drag is assumed by 2010. Although HLF has the potential to reduce fuel use by 15% or more, only a 9% efficiency gain is assumed due to the continuing difficulties in developing a practical system. In the efficiency case, ultra-high bypass engines are assumed to give a 10% efficiency gain, thermodynamic improvements provide a 15% gain, and advanced aerodynamics yield an 18% improvement. In this case, those are increased to 17%, 18% and 27%, respectively, certainly optimistic but not implausible estimates (for example, see Greene, 1992, Table 4).

The annual efficiency improvement rate for railroads is increased to 2.5%, still slightly lower than the 2.8% rate achieved over the past two decades. Waterborne freight's efficiency improvement rate is bumped up to 1% per year from 0.05% to reflect a 10% total efficiency gain achievable through improved hull designs and coatings. In fact, these modes have substantial potential to use alternative power plants and fuels, as reflected in the 2020 technology discussion below.

5.3.4 Comparison of Forecasts

The efficiency and high-efficiency/low-carbon scenarios indicate that advanced energy technologies could reduce emissions of greenhouse gases from transportation by 12-17% by 2010 and by 18-25% by 2015 (Table 5.7). Although these are large changes, they may appear modest compared to the changes in new vehicles, the "leading edge" of changes in the entire transportation fleet. Changing the technology of transportation requires turning over a vast stock of vehicles, and this requires decades. As a result, the impact of advanced technologies introduced between now and 2010 will only just begin to be felt in 2010 and will still not have achieved its full effect by 2015. This phenomenon can be most easily seen by comparing the fuel economy of new cars and light trucks to that of the entire fleet of light-duty vehicles. In the efficiency case in 2015, for example, new cars average 41.4 MPG and light trucks 31.9 MPG (EPA-rated fuel economy), but the fleet as a whole lags behind at 28.2 MPG (24.0 MPG onroad). Given enough time to turn over the stock of vehicles, the eventual light-duty fleet MPG will climb about one-third higher to nearly 38 MPG (32 MPG onroad). The time lag required for new technology to penetrate the light-duty vehicle fleet is a common feature of all modes. Thus, the energy savings and greenhouse gas reductions shown in Tables 5.7 and 5.8 for 2010 and 2015 reflect less than half of the ultimate savings that the technology introduced over this period will eventually achieve.

Passenger car and light truck fuel economy improvements are, in general, attributable to the combined effect of many fuel economy technologies rather than a single, dominant technology. A number of improvements to conventional engines combine to increase average new vehicle MPG in 2010 by almost 20% for passenger cars and by about 10% for light trucks. These include engine friction reduction, greater use of multi–valve engines, and variable valve timing and lift control. Substitution of lighter weight materials, aerodynamic drag reductions, various transmission improvements, and the combined effects of advanced lubricants, tires, and accessories, each contribute 2-5% gains. Of all the technologies added to the efficiency and high-efficiency scenarios, the lean-burn gasoline engines (DISC and 2-stroke) deliver the greatest fuel economy benefits, about 15% for passenger cars and 12% for light trucks. These numbers represent sales weighted average effects, taking into consideration the fact that even in 2010 new vehicles are not equipped with these technologies. Diesel and hybrid technologies each boost average new car and light truck fuel economy by about 5% in 2010, their smaller impact being due to their smaller market shares.

The sales weighted average impacts of nine classes of fuel economy technologies in the high-efficiency/low-carbon case are illustrated in Figures 5.7 and 5.8. The measured percent fuel economy gain applies to the impact of the technology on the average fuel economy of all new passenger cars or light trucks and, thus, takes into account the estimated market penetration for each category of technologies. In 2010, passenger cars get a considerably greater benefit from engine efficiency improvements than light trucks, but the gap narrows considerably by 2015. Although the DISC and 2-stroke technologies are the most significant new technologies in 2010, the gasoline fuel cell comes on strong by 2015. The impact of the fuel cell in 2010 is obviously limited by the assumption that it would be first introduced in 2007. The impacts shown in Figures 5.7 and 5.8 depend entirely on the cost, fuel economy benefit, and introduction date assumptions shown in Table 5.2, and the way the NEMS model translates those assumptions into market success. Thus, the graphs do not represent a prediction of what specific technologies will achieve, but rather an illustration of what could happen given the outstanding successes in fuel economy technology R&D, as reflected in our high-efficiency/low-carbon scenario assumptions.

The 23% gain for light-duty vehicles in 2015 is just slightly higher than the 21% and 22% improvements by freight trucks and rail in the efficiency scenario. Aircraft efficiency gains seem to lag behind at a mere 9% in 2015, but this is due to the fact that air passenger efficiencies increase the most (17%) in the business-as-usual case. In 2010, rail and air have made the greatest efficiency gains over 1997. This is consistent with the record of the past quarter century, during which time these two modes have led all others in energy-efficiency improvement.

Table 5.7 Transportation Sector Projections to 2010 and 2015 Efficiency Scenario (cont. next page)

	1997	2010		Change v. BAU	
	BAU	BAU	Efficiency	Change	% Change
Energy Use (quads)	25.5	32.3	29.3	-3.1	-9%
Carbon Emissions (MtC/Yr.)[1]	487	616	543	-73	-12%
Passenger Cars**	171	184	160	-24	-13%
Light Trucks	113	166	143	-23	-14%
Other Modes	203	266	240	-26	10%
Fuel Use by Fuel Type (quads)					
Motor Gasoline	15.1	18.0	15.2	-2.8	-15%
Cellulosic Ethanol (in motor gasoline)	0.0	0.0	0.5	0.5	***
Distillate	4.6	5.8	5.7	-0.1	-2%
Jet Fuel	3.6	4.7	4.2	-0.5	-11%
Residual	1.2	1.6	1.6	0.0	0%
Other	1.1	2.2	2.1	-0.1	-4%
Energy Use by Mode (quads)					
Light-Duty Vehicles	14.6	18.2	16.3	-2.0	-11%
Passenger Cars**	8.8	9.6	8.6	-1.0	-11%
Light Trucks	5.8	8.6	7.7	-2.0	-11%
Freight Trucks	5.6	6.8	6.3	-0.5	-8%
Air	3.6	4.7	4.2	-0.5	-11%
Rail	0.5	0.5	0.4	-0.1	-16%
Marine	1.7	2.3	2.3	0	0%
Pipeline	0.8	0.9	0.9	0	0%
Other	0.2	0.3	0.3	0	0%
Energy-efficiency Indicators					
New Car MPG^{+}	27.5	27.8	37.5	9.7	35%
New Light Truck MPG	20.5	20.6	27.1	6.5	32%
Light-Duty Fleet MPG	19.6	19.4	21.5	2.1	11%
Aircraft Efficiency (Seat-Miles/Gal.)	51.8	58.2	61.6	3.4	6%
Freight Truck Fleet MPG	5.6	6.0	6.8	0.8	13%
Rail Efficiency (ton-miles/1,000 Btu)	2.7	3.0	3.6	0.6	20%
Transportation Activity Levels (billions)					
Light-duty Vehicle Miles of Travel	2262	2762	2774	12	0%
Freight Truck VMT	173	237	238	1	0%
Commercial Air Seat-Miles	1116	1729	1608	-121	-7%
Rail Ton-Miles	1208	1459	1464	5	0%
Marine Ton-Miles	892	1047	1050	3	0%

Note: Because some light truck energy use is included in the freight truck sector, the totals by mode will not add to the totals by fuel type.

$^{+}$ After all scenarios had been completed, a minor error was discovered in the NEMS passenger car fuel economy technology input data. This error allowed four wheel drive improvements to be applied to certain categories of cars to which they are, in fact, not applicable. The overall effect on new car fuel economy is less than 0.3 MPG in 2010 and less than 0.5 MPG in 2015.

** Motorcycles, which are always less than 1%, are included with passenger cars.

Table 5.7 Transportation Sector Projections to 2010 and 2015 Efficiency Scenario (Continued)

	1997	2015		Change v. BAU	
	BAU	BAU	Efficiency	Change	% Change
Energy Use (quads)	25.5	34.0	28.7	-5.2	-15%
Carbon Emissions (MtC/Yr.)	487	646	532	-114	-18%
Passenger Cars	171	192	154	-38	-20%
Light Trucks	113	174	133	-41	-24%
Other Modes	203	280	245	-34	12%
Fuel Use by Fuel Type (quads)					
Motor Gasoline	15.1	18.7	13.5	-5.3	-28%
Cellulosic Ethanol (in motor gasoline)	0.0	0.0	0.4	0.4	***
Distillate	4.6	6.0	6.5	0.5	8%
Jet Fuel	3.6	5.0	4.2	-0.7	-15%
Residual	1.2	1.8	1.8	0.0	0%
Other	1.1	2.5	2.4	-0.2	-6%
Energy Use by Mode (quads)					
Light-Duty Vehicles	14.6	19.1	15.5	-3.6	-19%
Passenger Cars	8.8	10.0	8.3	-1.7	-17%
Light Trucks	5.8	9.1	7.2	-1.9	-20%
Freight Trucks	5.6	7.1	6.3	-0.8	-12%
Air	3.6	5.0	4.3	-0.7	-15%
Rail	0.5	0.5	0.4	-0.1	-20%
Marine	1.7	2.5	2.5	0.0	0%
Pipeline	0.8	0.9	0.9	0.0	0%
Other	0.2	0.3	0.3	0.0	0%
Energy-efficiency Indicators					
New Car MPG	27.5	27.9	41.4	13.5	48%
New Light Truck MPG	20.5	20.6	31.9	11.3	55%
Light-Duty Fleet MPG	19.6	19.5	24.0	4.5	23%
Aircraft Efficiency (Seat-Miles/Gal.)	51.8	60.6	66.1	5.5	9%
Freight Truck Fleet MPG	5.6	6.1	7.4	1.3	21%
Rail Efficiency (ton-miles/1,000 Btu)	2.7	3.2	3.9	0.7	22%
Transportation Activity Levels (billions)					
Light-duty Vehicle Miles of Travel	2262	2914	2937	23	1%
Freight Truck VMT	173	250	251	1	0%
Commercial Air Seat-Miles	1116	1923	1759	-164	-9%
Rail Ton-Miles	1208	1535	1540	5	0%
Marine Ton-Miles	892	1099	1102	3	0%

Table 5.8 Transportation Sector Projections to 2010 and 2015 High-Efficiency/Low-Carbon Scenario (cont. next page)

	1997	2010		Changes v. BAU	
	BAU	BAU	HE/LC	Change	% Change
Energy Use (quads)	25.5	32.3	27.9	-4.5	-14%
Carbon Emissions (MtC/Yr.)	487	616	512	-104	-17%
Passenger Cars**	171	184	147	-37	-20%
Light Trucks	113	166	132	-34	-21%
Other Modes	203	266	233	-33	-12%
Fuel Use by Fuel Type (quads)					
Motor Gasoline	15.1	18.0	13.9	-4.2	-23%
Cellulosic Ethanol (in motor gasoline)	0.0	0.0	0.7	0.7	***
Distillate	4.6	5.8	5.7	-0.1	-2%
Jet Fuel	3.6	4.7	4.0	-0.7	-14%
Residual	1.2	1.6	1.6	0.0	0%
Other	1.1	2.2	2.1	-0.2	-8%
Energy Use by Mode (quads)					
Light-Duty Vehicles	14.6	18.2	15.2	-3.0	-17%
Passenger Cars**	8.8	9.6	8.0	-1.6	-17%
Light Trucks	5.8	8.6	7.2	-1.4	-17%
Freight Trucks	5.6	6.8	6.2	-0.6	-9%
Air	3.6	4.7	4.1	-0.7	-14%
Rail	0.5	0.5	0.4	-0.1	-25%
Marine	1.7	2.3	2.3	-0.0	-1%
Pipeline	0.8	0.9	0.9	0.0	0%
Other	0.2	0.3	0.3	0.0	0%
Energy-efficiency Indicators					
New Car MPG+	27.5	27.8	43.1	15.3	55%
New Light Truck MPG	20.5	20.6	30.8	10.2	50%
Light-Duty Fleet MPG	19.6	19.4	23.2	3.8	20%
Aircraft Efficiency (Seat-Miles/Gal.)	51.8	58.2	64.6	6.4	11%
Freight Truck Fleet MPG	5.6	6.0	7.0	1.0	17%
Rail Efficiency (ton-miles/1,000 Btu)	2.7	3.0	4.0	1.0	34%
Transportation Activity Levels (billions)					
Light-duty Vehicle Miles of Travel	2262	2762	2806	44	2%
Freight Truck VMT	173	237	238	1	0%
Commercial Air Seat-Miles	1116	1729	1619	-110	-6%
Rail Ton-Miles	1208	1459	1467	8	1%
Marine Ton-Miles	892	1047	1051	4	0%

Note: Because some light truck energy use is included in the freight sector, the totals by mode will not add to the totals by fuel type.

+ After all scenarios had been completed, a minor error was discovered in the NEMS passenger car fuel economy technology input data. This error allowed four wheel drive improvements to be applied to certain categories of cars to which they are, in fact, not applicable. The overall effect on new car fuel economy is less than 0.3 MPG in 2010 and less than 0.5 MPG in 2015.

** Motorcycles, which are always less than 1%, are included with passenger cars.

Table 5.8 Transportation Sector Projections to 2010 and 2015 High-Efficiency/Low-Carbon Scenaro (Continued)

	1997	2015		Change v. BAU	
	BAU	BAU	HE/LC	Change	% Change
Energy Use (quads)	25.5	34.0	26.7	-7.3	-21%
Carbon Emissions (MtC/Yr.)	487	646	484	-162	-25%
Passenger Cars	171	192	134	-58	-30%
Light Trucks	113	174	114	-59	-34%
Other Modes	203	280	236	-44	-16%
Fuel Use by Fuel Type (quads)					
Motor Gasoline	15.1	18.7	11.2	-7.5	-40%
Cellulosic Ethanol (in motor gasoline)	0.0	0.0	0.7	0.7	***
Distillate	4.6	6.0	6.7	0.7	-12%
Jet Fuel	3.6	5.0	4.0	-1.0	-19%
Residual	1.2	1.8	1.8	-0.0	-1%
Other	1.1	2.5	2.2	-0.3	-12%
Energy Use by Mode (quads)					
Light-Duty Vehicles	14.6	19.1	13.8	-5.3	-28%
Passenger Cars	8.8	10.0	7.4	-2.6	-26%
Light Trucks	5.8	9.1	6.4	-2.7	-29%
Freight Trucks	5.6	7.1	6.2	-0.9	-13%
Air	3.6	5.0	4.1	-0.9	-19%
Rail	0.5	0.5	0.4	-0.2	-38%
Marine	1.7	2.5	2.4	-0.0	-1%
Pipeline	0.8	0.9	0.9	0.0	0%
Other	0.2	0.3	0.3	0.0	0%
Energy-efficiency Indicators					
New Car MPG	27.5	27.9	50.2	22.3	80%
New Light Truck MPG	20.5	20.6	37.8	17.2	83%
Light-Duty Fleet MPG	19.6	19.5	27.1	7.6	39%
Aircraft Efficiency (Seat-Miles/Gal.)	51.8	60.6	70.7	10.1	17%
Freight Truck Fleet MPG	5.6	6.1	7.5	1.4	23%
Rail Efficiency (ton-miles/1,000 Btu)	2.7	3.2	4.8	1.6	51%
Transportation Activity Levels (billions)					
Light-duty Vehicle Miles of Travel	2262	2914	2974	60	2%
Freight Truck VMT	173	250	252	2	1%
Commercial Air Seat-Miles	1116	1923	1923	-152	-8%
Rail Ton-Miles	1208	1535	1542	7	0%
Marine Ton-Miles	892	1099	1103	4	0%

Figure 5.7 Sources of Fuel Economy Improvements in High-Efficiency Scenario, 2010

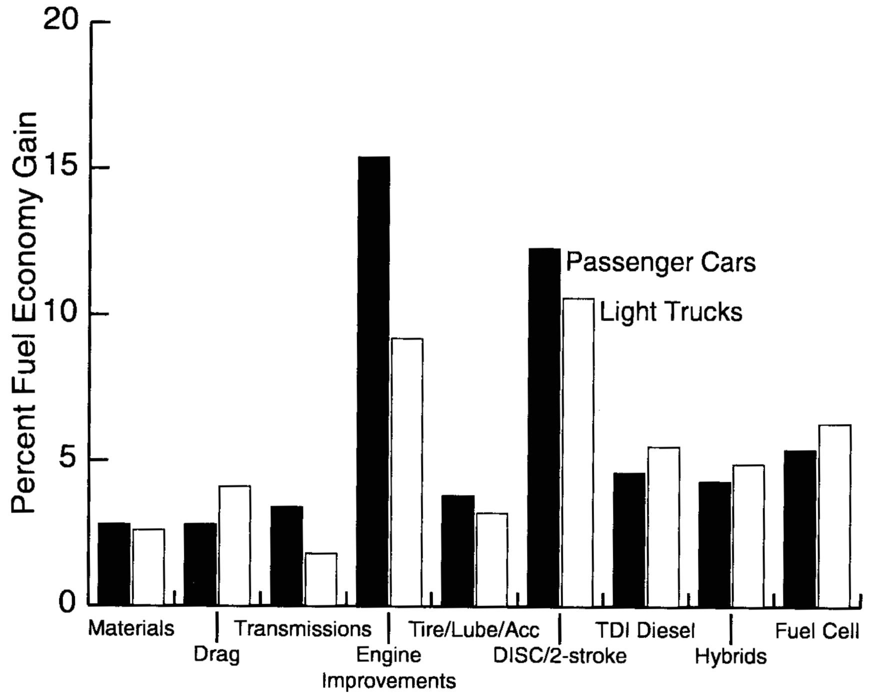
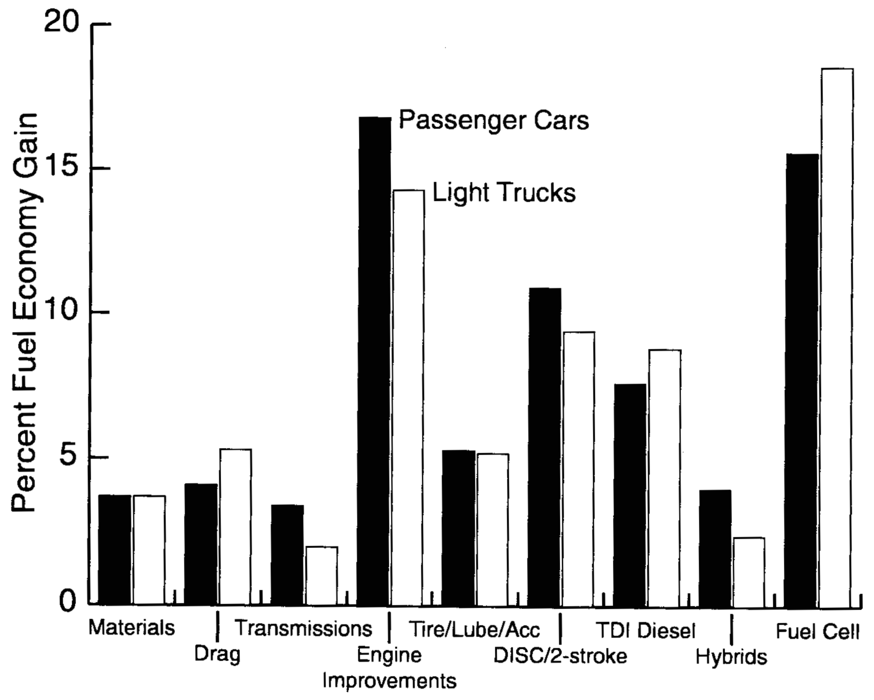


Figure 5.8 Sources of Fuel Economy Improvements in High-Efficiency Scenario, 2015



Transportation activity increases at moderate rates in the business-as-usual case and, indeed, in all the other scenarios as well. Transportation activity in the NEMS model is relatively insensitive to energy prices. In the business-as-usual scenario, light-duty vehicle travel increases by 22% from 1997 to 2010, an average annual rate of just 1.5%. In the high-efficiency/low-carbon scenario, the increase is 24%, reflecting a very small increase due to the lower fuel cost per mile of vehicle travel (1.7%/year). Growth from 2010 to 2015 is slower still, 1.1% per annum. Air travel is the fastest growing mode, with seat-miles growing at 3.4% annually through 2010 and slowing to 2.1% annually from 2010 to 2015. Efficiency improvements in the efficiency and high-efficiency/low-carbon scenarios include increased load factors (passenger-miles per seat-mile) so that seat-miles are actually 7% lower in the efficiency case than in the business-as-usual case in 2010 (Tables 5.7 and 5.8). Freight truck vehicle miles increase at a faster rate than light-duty vehicle miles, 2.5% per year through 2010, slowing to 1.1% from 2010 to 2015. These levels are almost unchanged by further increases in truck freight energy-efficiency. NEMS measures rail and marine activity in ton-miles, and these are up 21% and 17%, respectively, by 2010. Once again, the growth rate from 2010 to 2015 is at the much slower rate of about 1% per year.

The combined effects of moderately increasing transportation activity and significant efficiency gains are still not enough to reduce energy use or carbon emissions below present levels by 2010. Overall, transportation energy use in the business-as-usual case grows from 25.5 quads in 1997 to 32.3 in 2010 and 34.0 in 2015. The efficiency scenario lowers energy use by 9% in 2010 and carbon emissions by an additional 3%, due to the success of cellulosic ethanol as a gasoline blending component. Still, energy use is up 15% over the 1997 level, and carbon emissions are 12% higher. In 2015, however, energy use and carbon emissions are reduced compared to 2010 but still higher than in 1997. Although the 1997 version of the NEMS model does not forecast beyond 2015, it is reasonable to assume that energy use and emissions will continue to fall for a decade or so beyond 2015 as technological improvements penetrate the stock of transportation vehicles.

Motor gasoline use, on the other hand, is only 0.15 quads higher in 2010 than in 1997, and is a full 1.6 quads lower than the current level in 2015. The use of 0.4 quads of cellulosic ethanol and an equivalent shift to diesel are partially responsible for the reduction in gasoline consumption. Because cellulosic ethanol produces almost no net greenhouse gas emissions, it is far more effective than any fossil-based alternative fuel at reducing transportation's carbon emissions. Demand for distillate and jet fuel combined is up 1.7 quads in 2010 and is 2.6 quads higher than the 1997 levels in 2015. The slower growth of gasoline demand suggests a change in refinery operations would be required, but no analysis of the impacts of this change has been made.

The high-efficiency/low-carbon scenario achieves the milestone of reducing CO_2 emissions below 1997 levels, but by 2015 rather than 2010 (Table 5.7). In 2010, CO_2 emissions are 17% (a full 100 MtC per year) below the business-as-usual case, but still 4% above 1997 levels. With new cars at 43 MPG (EPA test value), new light trucks at 31 MPG, and the fleet average at only 27 MPG (23 MPG onroad), efficiency is improving rapidly and still has a long way to go. New passenger car MPG hits a fleet average of 50 in 2015 in this scenario, buoyed by market shares of 25-30% for hybrid vehicles, and 15-20% for turbo-charged direct-injection diesel vehicles. Two-stroke engines are also popular in this scenario, capturing about one-third of the small-car market. By 2015, all remaining new light-duty vehicles are equipped with DISC engines, the gasoline engine of today having been all but entirely squeezed out by newer technologies.

Yet even the high-efficiency/low-carbon case, with its breakthrough technology assumptions, illustrates how much time it takes to fundamentally change the technology of transportation energy use. Though fleet average light-duty vehicle MPG is up from 19.6 to 27.1 (onroad) by 2015, there is another 10.3 MPG to go before the fleet achieves equilibrium with the efficiency of new vehicles. Similarly, in the rail mode, use of fuel cells has penetrated only 5% of the stock of locomotives by

2010 and 15% by 2015. In most cases, the majority of CO_2 emission reductions have yet to be realized, even by 2015. The point is not that little can be done to reduce transportation's CO_2 emissions. The point is that if CO_2 emissions must be reduced, the sooner one gets started, the better.

5.3.5 Cost-Effectiveness of Light-Duty Vehicle Fuel Economy Improvement

The cost-effectiveness of technological changes that improve fuel economy is a very complex issue, depending not merely on the value of fuel savings and the increase in retail price, but on how each technology affects the performance, reliability, appearance and feel of a vehicle. Even such a seemingly simple matter as computing the value of fuel savings is not straightforward, since it depends on car buyers' expectations about future fuel prices, vehicle lifetime (or, alternatively, market valuation of remaining fuel savings when the vehicle is traded in or resold), consumer discounting of future savings, expectations about future depreciation of the vehicle's value, and expected utilization rates.

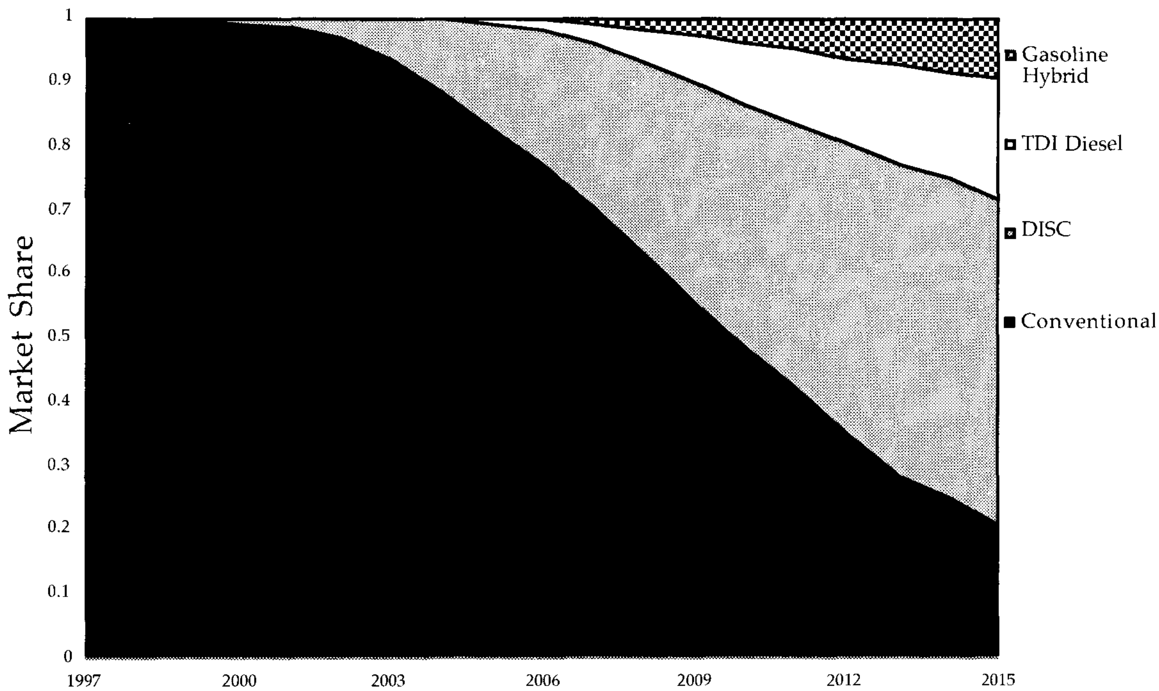
Technological advances are likely to create new opportunities to provide other benefits of importance to car buyers and to society. For example, multi-point fuel injection is generally held to be not cost-effective solely on the basis of fuel savings – yet every new car sold and nearly every new light truck is equipped with it. The reason for including fuel injection is that it improves drivability and also is a critical technology for meeting emissions standards. Technologies included in the efficiency scenarios also have the potential to create social benefits. By reducing oil consumption, they will decrease the volume of U.S. oil imports. By making it easier and cheaper to improve efficiency and substitute alternative energy sources for oil, these technologies will improve U.S. energy security. Technologies such as hybrid vehicles and fuel cells will help vehicles meet increasingly stringent emissions standards. Most importantly, technological advances will be essential to creating a sustainable world transport system.

The cost of supplying technologies is also not a simple matter, since it depends on the rate at which capital equipment must be replaced. If the rate of adoption exceeds the normal rate of turnover of manufacturing equipment, the costs of technological change increase. Also, new technologies must often be certified to meet safety and environmental standards, which takes time and involves some degree of risk. Consumers expect a high degree of reliability of vehicles, and this might be threatened by too rapid introduction of novel technologies.

For all these reasons, the NEMS model does not base technology adoption on a simple cost-effectiveness calculation, but rather attempts to simulate the complex process described above. The market penetration of fuel economy technologies is a function of cost-effectiveness, but is not solely determined by it. Market penetration follow an s-shaped curve that predicts 50% market penetration for precisely cost-effective technologies, with increasing or decreasing market share as cost-effectiveness increases or decreases, respectively. This simulates the fact that consumers are not identical in their valuation of technology (e.g., high mileage drivers such as sales representatives might tend to value fuel economy more than would average drivers), and that technologies have other characteristics that consumers may, or may not, value. Also, introduction is not immediate when cost-effectiveness is reached, but is rather phased in over time, simulating a normal process of retirement and replacement of manufacturing capital.

The phasing in of new technologies can be seen in Figures 5.9 to 5.11, which show the predicted market penetrations of engine technologies. Engine technology penetrations in the efficiency case are shown for passenger cars and light trucks in Figures 5.9 and 5.10. Although the DISC, TDI Diesel, and Gasoline Hybrid technologies eventually come to dominate the market, it takes about a decade for this to occur, allowing time for orderly introduction of the technologies. For comparison, the historical market penetration rates of fuel injection technologies are shown in Figure 5.11. Although it took less time for multi-point fuel injection to replace carburetted fuel systems, this technological change was urged on by emissions regulations. Nonetheless, as a point of comparison, it suggests that the rates predicted by the NEMS model are comparable to similar historical transitions.

Figure 5.9 Market Penetration of Advanced Engines for Domestic Passenger Cars - Efficiency Scenario



For all the reasons noted above, simple cost-effectiveness calculations based solely on incremental first cost and the value of future fuel savings can be misleading. Indeed, the NEMS model outputs do not include direct measures of the costs of technological changes or their value to vehicle purchasers. However, for light-duty vehicles, approximate technology cost estimates can be derived from the market shares of each technology and from the initial cost estimates. By comparing the weighted average cost of fuel economy technology in the efficiency and high-efficiency cases in 2010 with the weighted average cost in 1997 for the BAU case, we can obtain an estimate of the increase in retail price per vehicle due to the adoption of fuel economy technology. The incremental costs must be adjusted, however, to reflect the fact that a significant fraction of the potential MPG increase is used in the NEMS model to produce higher horsepower or increased vehicle weight, or to offset small MPG losses due to safety and emissions improvements. The cost adjustment is made by multiplying the full cost increase by the ratio of the actual MPG gain to the potential MPG. For example, for automobiles in the efficiency case, this ratio is 0.7. Using the same assumptions employed in the model to calculate cost-effectiveness, we can also estimate the value to the average consumer of the change in fuel economy. These estimates are summarized in Table 5.9.

Figure 5.10 Market Penetration of Advanced Engines for Domestic Light Trucks - Efficiency Scenario

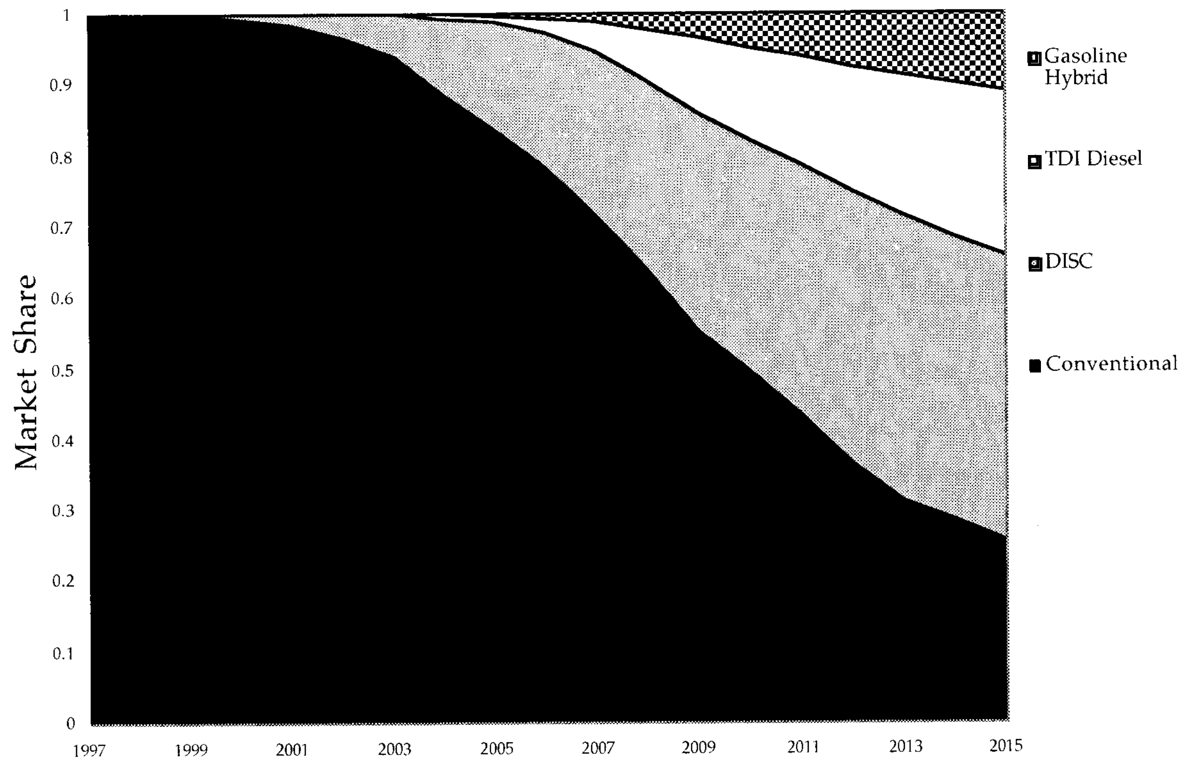


Figure 5.11 Penetration of Fuel Injection Technology

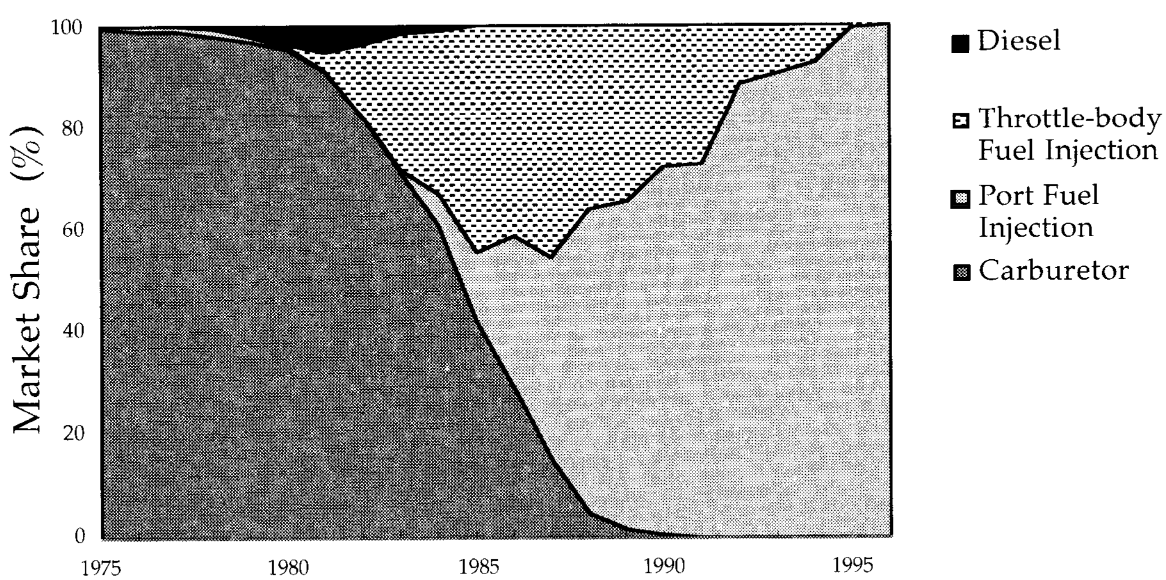


Table 5.9 Simple, Total Cost-Effectiveness Estimates for Light-Duty Vehicle Fuel Economy Technology

				Value of Fuel Savings to Consumer	
Scenario	MPG	Full Incremental Cost	Adjusted* Incremental Cost	10% Implicit Discount Rate	20% Implicit Discount Rate
Passenger Cars					
Business as Usual	27.5	$0	$0	--	--
Efficiency	37.5	$850	$600	$1,600	$1,000
HE/LC	43.1	$900	$900	$2,150	$1,350
Light Trucks					
Business as Usual	20.5	$0	$0	--	--
Efficiency	27.1	$800	$650	$1,950	$1,200
HE/LC	30.8	$950	$900	$2,700	$1,700

Gasoline prices assumed to remain constant at $1.20 per gallon. Vehicle usage rate of 15,500 miles per year, declining with vehicle age at 4% per year, and lifetime of 14 years. For calculating value to consumers, MPG estimates are reduced by 15% to reflect actual operating conditions.

*Adjusted to account for the use of fuel economy technology to increase horsepower instead of increasing miles per gallon.

The cost effectiveness estimates in Table 5.9 show that even at the higher 20% implicit discount rate, the light-duty vehicle fuel economy improvements are, as a whole, cost effective. This is not surprising since the NEMS model bases its technology market penetration predictions on a similar measure of cost effectiveness. Discounting future fuel savings at a lower rate of 10% only improves cost effectiveness.

Based on a simple comparison of incremental vehicle costs to the value of fuel savings to the consumer, fuel economy improvements in the efficiency scenarios appear to be cost-effective as a whole. Savings exceed costs for both discounting formulas shown. Choosing the correct discount rate is somewhat controversial since it depends on whether one believes that there are imperfections in the market for fuel economy. In the buildings chapter, for example, a 7% real rate is used to discount future fuel savings. We believe that a 20% implicit discount rate should be used for valuing light-duty vehicle fuel economy savings for the following reasons. When a consumer invests in vehicle technology to improve fuel economy, his or her decision-making calculus is analogous to a firm's capital investment decision. Indeed, consumers can be thought of as producing their own vehicle travel with inputs of vehicles, materials, and labor. In making this decision, the consumer must not only consider his or her discount rate (time preference or opportunity cost for money) but also the depreciation of capital. In other words, there are two costs of capital that must be accounted for, the time cost of money tied up in the capital and the depreciation of the capital. In general, the depreciation in a car's value is much greater during the first few years of its life. Indeed, a very significant depreciation occurs instantaneously when the first owner takes over possession from the dealer. After that time, the car is no longer "new". The initial owners of vehicles tend to hold them for about four years, on average, so that they bear a disproportionate share of the cost of depreciation.

The tendency of used car markets to "bundle" vehicle attributes, rather than price each separately may create a market imperfection that, when combined with the greater depreciation in value during the first few years of ownership, implies that new car buyers may reasonably be expected to demand a high rate of return in fuel savings for an investment in fuel economy technology. According to this hypothesis, with the exception of a few highly visible items, used car prices are determined by initial prices and the average rate of depreciation. That is, the value of fuel economy in the used car market is determined not so much by the present value of future fuel savings, as by the depreciated value of the initial investment in fuel economy. Assuming this market imperfection exists, the cost to the new car buyer of an investment in fuel economy technology is determined by the depreciation in its value over the first four years, rather than by the consumption of its fuel savings potential.

The combination of these two factors may lead new vehicle buyers to demand a rate of return much higher than the simple discount rate. If one assumes a 20% depreciation during the first year of vehicle ownership and 10%/yr. thereafter, then a consumer with a 7% real discount rate would, in effect, discount the full 14 years of fuel savings at about 15% to 16% to compensate for the cost of depreciation during the first four years of ownership. If future fuel savings are computed using the average usage rate for new vehicles, then future savings must be further discounted by 4% to 5% per year to reflect the typical rate of decline in vehicle use with age. Taken together, these factors imply that a new car buyer may appear to behave as if his discount rate for valuing future fuel savings were 20%, when in fact his simple real discount rate is only 7%.

These rough estimates should be treated with considerable caution. First, they represent a comparison of total costs of fuel economy changes with total benefits, taxes included, rather than the more correct comparison of marginal costs and benefits, excluding taxes. Markets will, in theory, stop improving fuel economy when the marginal costs equal the marginal benefits. In general, this will be at a lower level of fuel economy than the point at which total costs equal total benefits. Second, the NEMS model represents technology adoption as a more complex process than a simple computation of monetary costs and benefits, and attempts to simulate actual market behavior. Thus, the calculations reported above do not correspond to the NEMS technology adoption methodology.

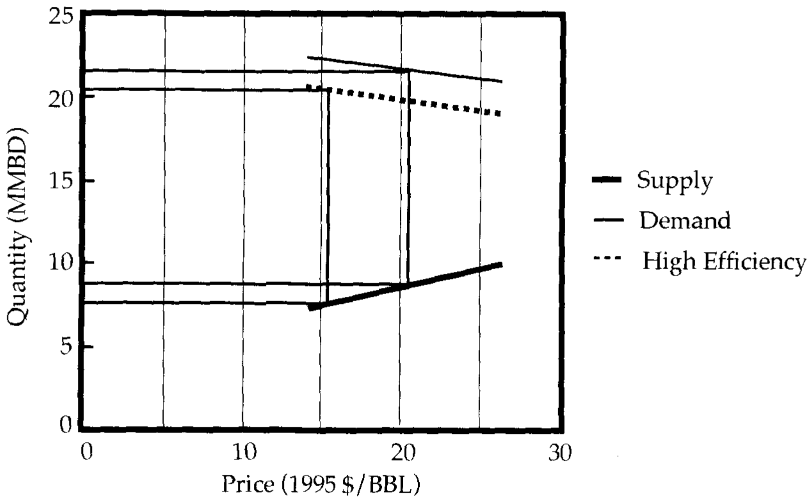
5.3.6 Oil Imports and Oil Market Benefits

The reductions in energy use achieved in the efficiency and high-efficiency/low carbon scenarios represent significant reductions in U.S. petroleum demand which should result in reduced U.S. oil import dependence and lower oil prices to consumers. Because of transportation's continuing dependence on petroleum in the business-as-usual scenario, 95% of transportation energy is still derived from petroleum in 2010. In the BAU scenario, transportation uses 30.6 quads (14.5 million metric barrels per day (MMBD)) of petroleum products. Technological advances contained in the efficiency scenario reduce petroleum consumption by 3.4 quads (1.6 MMBD) in 2010, and those in the high-efficiency/low-carbon scenario produce total oil savings of 4.9 quads (2.3 MMBD).

Lower U.S. oil consumption due to more energy-efficient technology and substitution of cellulosic ethanol should reduce U.S. oil imports, or reduce world oil prices, or both. The exact world oil market response is indeterminate because it depends on the actions of the OPEC cartel. In a competitive world oil market, the response to reduced U.S. demand could be predicted based on knowledge of the U.S. and rest-of-world supply and demand curves for oil. But because the cartel's supply does not necessarily follow the rules of competitive market behavior there is, in effect, no OPEC oil supply curve. Faced with reduced demand, competitive producers would lower prices, encouraging demand and driving out the higher cost producers until a new equilibrium were reached. But a cartel can choose to cut production, raise production, or do nothing, making the ultimate outcome uncertain. Cutting production would raise world oil prices but the cost to OPEC would be loss of market share, a key determinant of market power.

No matter what the OPEC cartel chose to do, however, either U.S. imports would fall, or oil prices would fall, or both, as a result of the technological advances reflected in the efficiency and high-efficiency/low-carbon scenarios. This is illustrated in Figure 5.12, which shows U.S. long-run supply and demand curves for petroleum derived from the 1997 Annual Energy Outlook's Low, High, and Reference Oil Price Cases for 2010 (EIA, 1996b, Table C11). The curves clearly show that at the reference case oil price of $20.41 per barrel, domestic supply and demand curves do not intersect, with the result that the 12.9 MMBD shortfall must be imported.

Figure 5.12 U. S. Oil Supply and Demand in 2010



The advanced technologies of the high-efficiency/low-carbon scenario shift the demand curve towards lower demand, and may also change its slope (perhaps making demand more responsive to price). If we assume that the world price of oil does not change (to achieve this result, OPEC would have to cut production by an amount roughly equivalent to the reduction in U.S. consumption), then U.S. imports would be lower by about 2 MMBD. If OPEC maintains previous production levels or increases its output, world oil prices would fall. As prices fall, U.S. domestic supply will decline and demand will increase, pushing imports back up. However, to achieve the original level of imports (12.9 MMBD), prices would have to fall by about $5 per barrel (given the supply and demand curves shown in Figure 5.12). The $5/bbl. price cut would reduce the total cost of oil to the economy by about $35 billion, and reduce the cost of oil imports by about $20 billion, in comparison to the AEO97 reference case. The possible outcomes are: 1) U.S. imports are reduced by 2.3 MMBD or more, 2) world oil prices fall by about $5/bbl or more, or 3) a combination of reduced imports of up to 2.3 MMBD and a price decrease of up to $5/bbl. occurs.

5.4 R&D POTENTIAL FOR ADVANCED TECHNOLOGIES IN 2020

5.4.1 Light-Duty Vehicles

Many of the advanced technologies that have the potential to impact U.S. automotive fuel use after 2010 or 2020 need considerable research and development work before they can attain commercialization. The federal government has supported work on many of these technologies for more than 20 years, beginning with the Energy Policy and Conservation Act of 1975. The current U.S. R&D effort on the more exotic of the new technologies has been characterized as "the most comprehensive, best organized, and best funded in the world" (U.S. Congress, OTA, 1995). Nevertheless, over the years, federal funding for vehicle technology R&D has been erratic, and there are continuing budget battles over funding for DOE's Electric and Hybrid Vehicle Program and the PNGV as a whole. As noted above, the National Research Council Committee that is reviewing the PNGV program has stated in no uncertain terms that they believe the program is seriously under-funded relative to its ambitious goals.

The OTA identified several R&D areas that will require considerable new resources including: safety; analysis and development of infrastructure for manufacturing, refueling, servicing, recycling, and so forth; and development of new standards for new materials and fuels (U.S. Congress, OTA, 1995). Also, OTA concluded that the current federal program may not take appropriate advantage of the innovative capabilities of small business, especially with budget pressure on the National Institute of Science and Technology's Advanced Technology Program and other R&D efforts that focus on smaller companies.

Although there are many hurdles to overcome, a strong R&D effort coupled with a market or regulatory incentive to improve fuel economy should be capable of producing, by 2020 or earlier, mid-sized vehicles with fuel economies in the 60-80 MPG range and performance similar to current vehicles – that is, "PNGV territory." Note that continuing fleet increases in power and performance will tend to reduce future fuel economy potential, since generally there is a direct tradeoff between performance and fuel economy. An optimistic vision of a potential high-efficiency/low-carbon vehicle in 2020, assuming the necessary breakthroughs in a number of areas (e.g., manufacturing processes for composite materials, two orders of magnitude reduction in fuel cell costs) would combine the following characteristics:

- Highly aerodynamic design with C_d of 0.22 or below;
- Lightweight body with composite body structure (safer alternative: optimized aluminum);
- Ultra-low rolling resistance tires, CR of 0.005 (about half that of today's tires);
- Hybrid drivetrain with lightweight, highly efficient storage device (ultracapacitor or flywheel) and electric motor/controller;
- Fuel cell powerplant with advanced hydrogen storage or efficient fuel reformer (safer alternatives: DISC engine or DI diesel with lean NO_X catalysts); and
- Use of high-efficiency/low-carbon accessories and low-energy-use design (e.g., advanced window coatings and insulation).

The current PNGV program is addressing many of the remaining R&D roadblocks though some need considerably more attention and the solution to others might be accelerated with greater resources. For example, development of manufacturing processes for composites has been hit hard by budget cutbacks; as noted, without major breakthroughs, composites will likely be too expensive to play a major role in vehicle light-weighting. In addition, there is some concern that Japanese and European firms are devoting more resources to DISC and DI diesel engines than are U.S. companies, and these engines may play a critical role in future high-efficiency/low-carbon vehicles, especially if fuel cell development is delayed or is unsuccessful at reducing costs sufficiently for commercialization.

Fuel cells are widely believed to be the most attractive powerplant option for future vehicles, and recent progress in increasing their power density and lowering costs through reducing their platinum requirements has been extremely promising. Nevertheless, as discussed previously, many hurdles remain, and their costs must decline remarkably for them to compete successfully with internal combustion engines. In fact, they would revolutionize the power generation industry long before they reached the $30/kW level of ICEs.[13]

Although some may view a fuel cell hybrid vehicle as an "ideal" vehicle, there are sufficient uncertainties in the potential of the technologies needed for such a vehicle, and sufficient heterogeneity in regional requirements and markets, to imply that an ideal R&D program in light-duty vehicle technologies should be a broad program incorporating a range of alternative technology pathways to high vehicle efficiency and low emissions. A breakthrough in high-specific-energy battery technology coupled with significant progress in electric motors and power electronics, for example, could put large numbers of efficient electric vehicles into many urban markets; in some of those markets (e.g., California) both the overall emissions effects and the greenhouse gas emissions effects could be extremely positive. Similarly, breakthroughs in on-board storage technology for natural gas might allow substantial penetration of natural gas vehicles into many markets, although the positive greenhouse gas emissions impact of such vehicles would likely be substantially less than for EVs or fuel cell hybrids.

5.4.2 Freight Trucks and Locomotives

The diesel cycle engine will dominate the freight truck sector at least until 2020 because of its high thermal efficiency, potential fuel flexibility, and durability. DOE's Office of Heavy Vehicle Technologies (OHVT) within the Office of Transportation Technologies is attempting to develop the enabling technologies needed to achieve fuel flexibility, ultra-low emissions, and high fuel efficiency in all classes of trucks, buses, and other heavy vehicles such as off-highway vehicles. The typical new Class 8 tractor trailer in 2020 is expected to achieve an on-road fuel economy of over 10 MPG, compared to about 7 MPG today, assuming a high-efficiency/low-carbon, low emission diesel cycle engine (thermal efficiency of at least 55% at rated speed and load at the flywheel) and other technologies such as reduced aerodynamic drag, low rolling resistance tires, and lightweight materials (such as magnesium) become an economic reality.[14] While many of these technologies have already been demonstrated to a limited extent, a key enabler is a durable highly efficient NO_X catalyst capable of operating at high-efficiency/low-carbon in an oxidizing atmosphere.[15] Fuel reformulation is envisioned, as well as nonpetroleum fuels, during this period (2000-2020).

However, as the efficiency of the diesel cycle becomes fully exploited (thermal efficiencies of over 63% will be highly unlikely), the hydrogen fuel cell, unconstrained by the Carnot cycle, may be the next powerplant of choice for freight trucks, locomotives, and passenger cars. Significant R&D efforts at DOE have enabled the demonstration of methanol-fueled fuel cell buses and other vehicles. However, significant development of the fuel cell itself, power management strategies, and hydrogen fuel production, distribution and storage are required, and economical solutions are hard to envision before 2020. Particularly problematic are the low cost, efficient production, delivery, and storage of hydrogen fuel (carbon-containing fuels significantly degrade fuel cell thermal efficiency – in many cases to efficiencies below that of current-production diesel engines). The fuel cell powerplant, combined with low aerodynamic drag, low rolling resistance tires, and lightweight materials may raise Class 8 tractor trailer fuel efficiency to 15 MPG or more. Locomotive engines may be an ideal test bed and an early entry for fuel cell powerplant technologies, because sizes needed (4000 hp-equivalent) are on the scale of smaller stationary electrical power generation plants which are already commercial. In addition, locomotives are already driven by computer-driven electric motors for traction control.

5.5 SUMMARY

Cost-effective or near cost-effective technologies and alternative energy sources have the potential to significantly restrain the growth of the U.S. transportation sector's greenhouse gas emissions through 2010. There remains a substantial reservoir of proven technology for improving motor vehicle fuel economy, and technologies that are very nearly market-ready (such as the DISC engine with lean-NO_X catalytic converter) will almost certainly further expand the potential to increase MPG by 2010. New technologies and operational efficiency gains hold out similar potential for air passenger travel and for truck and rail freight. Ethanol derived from cellulosic feed stocks instead of grain could also make a significant contribution by 2010 as a blending component for conventional gasoline if cost reductions foreseen by energy researchers are achieved. Overall, the combined impact of such technologies could be to reduce greenhouse gas emissions by 10% in 2010 and by almost 20% in 2015, relative to the business-as-usual case. If important breakthroughs can be achieved in fuel cells and other key technologies, transportation's greenhouse gas emissions in 2015 could be held below current levels.

In the business-as-usual case, transportation energy use grows from 25.5 quads in 1997 to 32.3 in 2010 and 34.0 in 2015. Carbon dioxide emissions, in million tonnes of carbon, increase from 487 in 1997 to 616 in 2010, and to 646 in 2015. As mentioned earlier, the business-as-usual case anticipates rates of growth in transportation activity that are slow by historical standards. The actual outcome could easily be 10% higher. The efficiency case holds transportation energy use to 29.3 quads in 2010 and 28.7 in 2015. Accordingly, carbon emissions grow to only 543 MtC in 2010 and 532 in 2015. The fact that emissions are lower in 2015 than in 2010 reflects the fact that changing the technology of transportation energy use requires the orderly turnover of durable capital stock. The high-efficiency/low-carbon scenario holds 2010 carbon emissions from transport to 512 MtC, and reduces 2015 emissions to 484 MtC, just slightly below the 1997 level.

Changes in the mix of transportation fuels in the three 2010 scenarios are summarized in Table 5.10. Although petroleum fuels are still the predominant source of energy for transportation, use of alternative fuels expands in all three scenarios. Natural gas consumption for transport grows from 0.75 TCF in 1997 (about 98% of which is used in natural gas pipelines) to roughly 1.2 TCF in 2010. In 2010 pipelines still account for 70-75% of natural gas use, but CNG vehicles consume about 0.25 TCF, and natural gas used to produce methanol for motor fuel accounts for nearly all of the rest. Biofuels in the form of cellulosic ethanol come on strong in the efficiency and high-efficiency/low-carbon scenarios, providing from one-fourth to one-third of an MMBD oil equivalent. In accord with the AEO97 reference case projections, all scenarios foresee substantial increase in electricity use, essentially all going to electric vehicles. The lower levels of electricity use in the efficiency and high-efficiency/low-carbon scenarios, like those of natural gas use, are due to the general improvements in vehicle technology in those scenarios.

Carbon emissions by mode are summarized in Table 5.11. Light-duty vehicles account for the vast majority of carbon emissions reductions versus the business-as-usual case, with significant contributions also being made by trucks and commercial aircraft. Rail freight shows the greatest relative reduction, while emissions from shipping, military and "other" are essentially constant across the three scenarios.

Table 5.10 Transportation Energy Use by Fuel Type

Fuel	1997	2010 BAU	2010 Efficiency	2010 High-Efficiency
Petroleum Fuels (MMBD)	11.77	14.59	12.91	12.18
Natural Gas (TCF)	0.75	1.22	1.19	1.16
Biofuels (MMBD OE)	0.001	0.04	0.25	0.34
Electricity (MMBD OE)	0.04	0.23	0.22	0.20

Note: Petroleum fuels converted to million barrels per day oil equivalent using a heat content of 5.738 MMBtu/barrel. Natural gas includes pipeline fuel and natural gas used to produce methanol for use as a neat fuel, but does not include natural gas used to produce methanol for use in Methyl Tertiary Butyl Ether. It is assumed that, to produce one quad of methanol, 1.44 quads of natural gas are required. For electricity generation, 3.38 quads of primary energy are assumed to be required for each quad of electrical energy consumed.

Table 5.11 Carbon Emissions in 2010 (MtC)

	1997	2010 BAU	2010 Efficiency	2010 High-Efficiency
Light-Duty Vehicles	278.7	346.3	297.3	273.0
Freight Trucks	73.3	95.0	83.4	80.9
Freight Rail	8.9	9.6	8.1	7.1
Shipping	30.8	42.7	42.3	41.6
Air Transport	60.0	83.5	72.9	69.6
Military, Transit, Other	35.3	39.0	39.3	39.3
TOTAL	486.9	615.9	543.3	511.5

Note: Breakdown into modal carbon emissions based on emissions factors taken from EIA (1996d) and DOE (1996)

Most of the reduction in energy use and carbon emissions comes from light-duty highway vehicles. There are four reasons for this. First, light-duty vehicle technology has been far more intensively studied, so that a great deal more is known about the technological potential for this mode. Second, the level of expenditure on technology R&D is greatest for this mode, with the possible exception of aerospace R&D, including defense aerospace. Third, the commercial modes are believed to be more sensitive to fuel costs and more aggressive in the adoption of energy-efficient technology. Therefore, the rates of energy-efficiency improvement in the business-as-usual case are higher for these modes. Finally, light-duty vehicles simply use more energy than any other mode: 60% in the business-as-usual case. The other modes cannot be ignored, however, and should probably be given much greater attention with respect to R&D investment.

Although technological improvements have the potential to cost-effectively restrain greenhouse gas emissions from transportation, it is not likely that the changes will come about without a major public policy initiative. There are two reasons for this. First, the problems posed by greenhouse gas emissions are what economists term a classical public good externality. This means that the market economy will not provide the right price signals either for the development or the adoption of low-carbon technologies. Second, the AEO97 projections foresee a world where fossil fuels are abundant, available and inexpensive. In particular, none of the oil market upheavals of the past quarter century are present in the forecast. As a result, there are no other economic incentives to encourage either energy-efficiency or alternative fuels. In such an environment, it is not reasonable to expect either that appropriate technology will be developed or that success in the marketplace will result.

As a result, the efficiency case is based on the assumption that policies are implemented to promote the development of cost-effective low-carbon technologies and to spur the adoption of these technologies. In our view, this would include at a minimum a greatly increased public sector investment in R&D addressing energy-efficient and low greenhouse gas technologies, perhaps two to ten times the current level of effort. There are other public interests in developing such technologies (e.g., energy security and environmental sustainability) that, we believe, could easily justify such a level of investment. But policies to insure the adoption of low-carbon technologies in the market would also be necessary. It is not the purpose of this study to recommend what those policies should be; nonetheless, we are obliged to point out that meaningful policies will be necessary.

Indeed, technology has enormous potential to reduce transportation's greenhouse gas emissions. Cost-effective technological change will take time however, and its full effects will not be felt for two decades or more. Because the problems that may result from increased carbon emissions affect the global environment, significant reductions will demand meaningful public policy initiatives. These must include a greater effort to develop low-carbon technologies and a commitment to implement policies that will insure their adoption in the market.

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ENDNOTES

[1] This rate applies to the period 1973 (18.605 trillion Btus) to 1985 (20.067 trillion Btus). Source is Table 2.2, Monthly Energy Review, April 1997, DOE/EIA-0035(97/04), U.S. Department of Energy, Energy Information Administration, Washington, DC.

[2] This is a summary report. The full report, which presents this material, was not published due to OTA's closure, but it is now available as part of a three-CD set that contains all of OTA's reports since its inception. U.S. Congress, Office of Technology Assessment, *OTA Legacy: 1972 through 1995*, U.S. Government Printing Office, Washington, DC, Stock no. 052-003-01457-2, $23 U.S.

[3] The Toyota AXV5, with a C_d of 0.20, appears to avoid sacrifices in interior and cargo space. Removing its wheel skirts, which might inhibit maintenance and restrict the vehicle's turning circle, would likely raise its C_d to about 0.22. Because the vehicle's underbody cover adds weight, the net positive effect on fuel economy will be reduced somewhat (U.S. Congress, OTA, 1995).

[4] In particular, requirements for 0-60 mph acceleration and sustained gradeability.

[5] Also referred to as compression ignition direct injection (CIDI) engines and turbocharged direct injection (TDI) diesel engines.

[6] An accurate cost comparison would have to account for the transmission needed by the engine versus the electric motor needed to convert the fuel cell's output electricity into shaft power. Also, the fuel cell drivetrain may need a powerful battery to drive the vehicle until the cell can warm up.

[7] At about 3700 psi storage pressure, storage volume for hydrogen is about 5 times that needed for gasoline (Oei, 1997).

[8] An additional cost may be the loss in system efficiency associated with onboard reforming as well as the original refining of the gasoline. However, onboard hydrogen storage has energy costs in the form of hydrogen production (probably at a large scale, and more efficient than the onboard reformer) and pressurization if stored in high pressure tanks.

[9] Despite what is implied in the NEMS Transportation Model documentation, we were informed by Mr. David Chien, principal in charge of the Transportation Model, that the model's calculations were in 1987$. Thus, $8 in 1995 dollars equates to approximately $6 in 1987 dollars.

[10] For carbon only; or $.08-$0.16 per gallon if the tax applies to all greenhouse gases, on a carbon equivalent basis.

[11] Communication from Margaret Singh of Argonne National Laboratory, April 3, 1997. Her calculations were made using the August, 1993 version of M. A. Delucchi's greenhouse gas emissions model and exclude any vehicle efficiency gains which might occur with the use of an ethanol vehicle.

[12] An alternative approach would have been to introduce these technologies using the Transportation Model's alternative fuel vehicle capabilities. This approach was not taken on the grounds that diesel is more conventional than an alternative fuel. Consumers are familiar with it, it is widely available and, especially for the advanced, clean, TDI technology considered here, its performance would be essentially identical to that of a gasoline vehicle.

[13] Actually, for an accurate comparison, an ICE plus a transmission and inexpensive fuel tank should be compared with a fuel cell, hydrogen storage or liquid fuel storage/reformer system, battery for warmup power and power buffer, and electric traction motor, making the task of commercializing fuel cells all the more onerous.

[14] The Class 8 truck is very efficient already. Considering an energy per ton-mile measure of performance, an equivalent passenger car needs to travel about 140 miles on a gallon of gas to be as

efficient as a 7 MPG Class 8 truck.

[15] This technology is required for direct-injection gasoline engines as well.

Chapter 6

THE ELECTRICITY SECTOR'S RESPONSE TO END-USE EFFICIENCY CHANGES

6.1 INTRODUCTION

Electricity consumption accounts for about 36% of both total primary energy consumption and carbon emissions in the United States (EIA 1996a). As a consequence, converting efficiency-induced electricity savings in the residential, commercial, and industrial sectors into carbon reductions is a critical part of this study.

This task is complicated by several factors. First, the U.S. electricity industry is in the midst of a major restructuring, from a highly regulated, vertically integrated industry to a largely competitive, deintegrated industry. Because this transformation is far from complete, it is difficult to predict the structure and operation characteristics of electricity markets for the year 2010. Second, electricity production in the year 2010 will depend on the generating units that are retired, repowered, and constructed between now and then, as well as on how those units are operated in 2010. The decisions made by the profit-maximizing owners of individual generating units are likely to be different than the cost-minimizing decisions made in the past by utility owners of large generation and transmission systems. As a result of these changing dynamics of capacity expansion and system operation, one cannot assume that the average and marginal carbon intensities of electricity use (tonnes of carbon/GWh) will be the same in 2010 as they are today. Indeed, they are likely to be quite different. Third, electricity prices in the year 2010 are likely to vary from hour to hour based on current spot-market prices; consumer response to such time-varying prices is likely to be substantial but is largely unknown.

The next section describes some of the key changes in the structure of the U.S. bulk-power system that are likely to occur over the next decade. Section 6.3 describes the Oak Ridge Competitive Electricity Dispatch (ORCED) model that is used here to project the characteristics of the electricity sector in the year 2010. Section 6.4 compares ORCED's projections for the electricity sector with those developed by EIA in its *Annual Energy Outlook 1997* (AEO97). We then develop a competitive-electricity market case for 2010, which is used as the base case against which the efficiency and high-efficiency/low-carbon cases are compared.

6.2 BACKGROUND

In response to the 1992 Energy Policy Act, the Federal Energy Regulatory Commission (FERC) issued a major order (Order 888) in April 1996, which it slightly revised in March 1997. This order requires utilities to unbundle their generation and transmission services. A utility cannot offer preferential transmission pricing for electricity generated by its own power plants. A key purpose of this order is to eliminate problems associated with vertical market power in bulk-power markets and thereby assure open access to the nation's transmission facilities.

Other factors are also forcing the U.S. electricity industry to change. These factors include low natural gas prices (both today and over the next 10 to 15 years), substantial improvements in the efficiency of gas-fired combustion turbines, and broad public sentiment to deregulate economic sectors wherever possible.

We see a future in which the generation sector will be driven primarily by competitive forces rather than by regulatory mandates. Decisions on whether, when, and where to build, repower, or retire generating units will be made by investors, not by regulators.[1] Historically, vertically integrated utilities have planned, built, and operated power plants to minimize the life-cycle costs of the entire electric-power system over a long time (e.g., 20- to 30-year horizon). In tomorrow's competitive environment, this decision rule will be replaced by one that emphasizes the profitability of individual generating units over a much shorter time horizon, using a higher discount rate to reflect the increased riskiness of power-plant ownership.

Our view of the future calls for most of today's utility-operated control centers to be replaced by *independent* system operators (ISOs) that cover larger areas. As a consequence, the number of control areas will decline from about 140 to perhaps only 20 to 50. Because these ISOs perform a monopoly function, they will be regulated by FERC.

Similarly, transmission will remain a monopoly function, also regulated by FERC. Increasingly, transmission will be separated from generation. Today, FERC requires utilities to "functionally" unbundle generation from transmission. In the future, utilities will increasingly divest themselves of their generation assets and will become "pure" transmission or transmission-plus-distribution utilities. In this environment, transmission will become a common carrier.

6.3 MODEL DESCRIPTION

ORCED is an expanded version of part of a previously developed model called ORFIN (Oak Ridge Financial Model) (Hadley 1996). Whereas ORFIN is a comprehensive electric-utility planning model, ORCED deals only with generation. We developed ORCED to aid in the analysis of the operation of competitive (as opposed to the traditional regulated) bulk-power markets. The model allows the following issues to be examined:

- Horizontal market power: concentration of generation assets among a few owners;
- Generator profitability: which units will be retired because their expected revenues will not cover the sum of their fuel costs, variable operations and maintenance (O&M) costs, and (avoidable) fixed O&M costs, as well as repowering and new construction decisions;
- Carbon emissions and other environmental effects of changes in the U.S. bulk-power sector; and
- Optimal mix of new and existing generators, including new generating technologies.

The model is structured to allow simulation of different bulk-power market structures. In particular, the user can specify various generation pricing schemes:

- An energy-only spot price as proposed by the three California investor-owned electric utilities. When unconstrained demand exceeds available supply, what would otherwise be unserved energy is "curtailed" because spot prices rise sufficiently to suppress demand to match the level of available generating capacity. The user simulates this situation by specifying a value for the price elasticity of demand during these time periods. ORCED uses the amount of demand to be curtailed and the price elasticity to calculate the value of unserved energy in ¢/kWh.[2]
- An energy-only spot price plus the loss-of-load probability (capacity) component used in the United Kingdom. Here, the user specifies a value for unserved energy (e.g., 200¢/kWh), which

the model multiplies by the hourly value of the loss-of-load probability to produce a time-varying increment to the energy-only spot price.

- An energy-only spot price plus a capacity reservation price (in $/kW-year), as proposed by the PJM Interconnection and the New England Power Pool. In this case, the user specifies an amount of generating capacity needed for planning reserve, which determines the annual capacity payments (in $/kW-year) required.

We are using ORCED to examine the issues listed above as functions of the following factors (in addition to the pricing schemes noted above):

- Characteristics of individual generators: type of unit, differences in capital and other fixed costs ($/kW-year) vs. fuel and variable O&M costs (¢/kWh), dispatchability (e.g., fully dispatchable coal plant vs. must-run nuclear unit vs. stochastic wind plant), forced and planned outage rates (%).

- Customer and load characteristics: shape of load curve, price elasticities of demand, value of unserved energy.

- Generating-resource portfolio: mix of generating units and relationship between available generating capacity and unconstrained peak demand.

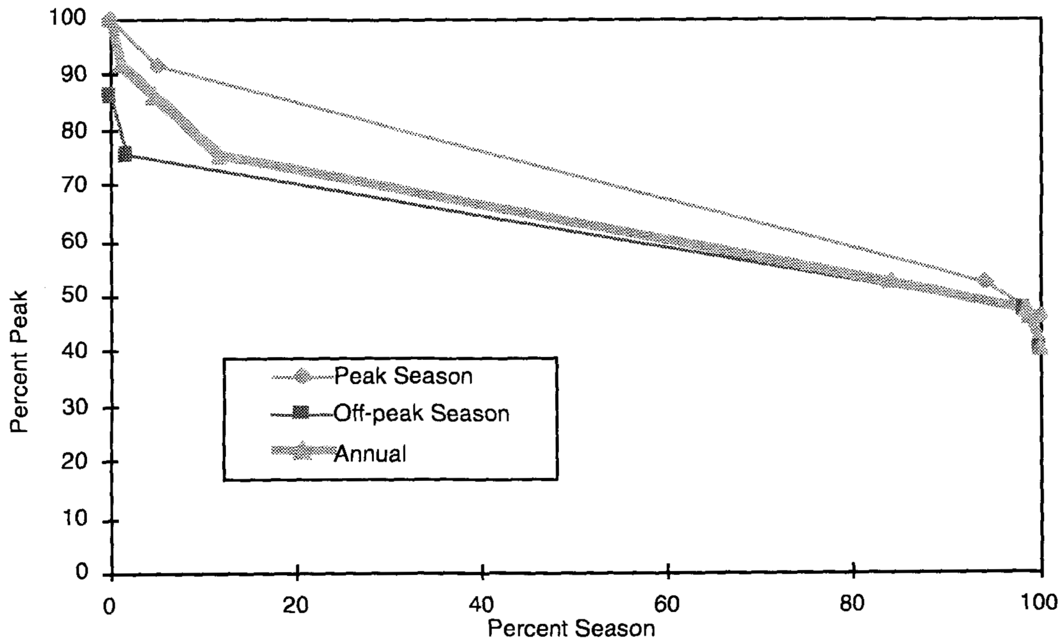
ORCED includes a production-costing model that uses load-duration curves rather than chronological loads as inputs. The model is run twice for each year of simulation, once for an on-peak season and a second time for an off-peak season (Figure 6.1). We define the on-peak season as June through August, and the off-peak season as the remaining nine months (September through May), although the model can accept alternative definitions of the two seasons. The model can incorporate disaggregate inputs on loads and load shapes for the residential, commercial, and industrial customer classes. Data on these class loads are aggregated for use within ORCED, which builds and dispatches generating units to meet aggregate load.

A load-duration curve is created by ordering demand (in MW) in terms of magnitude from highest to lowest. The resultant curve shows the percentage of time that demand exceeds a particular value, ranging from the one-hour peak demand down to the minimum demand.

Use of a load-duration curve to calculate production costs is much simpler and computationally much less burdensome than use of chronological loads (i.e., hour by hour loads). This simplification, however, has a price: because it obscures the timing of loads, one cannot accurately calculate production costs on the basis of generating-unit details, such as minimum and maximum loading points, startup times and costs, and minimum shutdown times. To partially remedy these problems, ORCED analyzes production costs using the two load-duration curves, one for the three-month summer peak period and the other for the nine-month off-peak period. ORCED also simulates the effects of startup costs for those units with capacity factors of less than 10%.

For each season, the model has available to it 26 generating units. The first 25 units are characterized in terms of capacity, forced and planned outage rates, fuel type, heat rate, variable O&M costs, fixed O&M costs, and annual capital costs (based on initial construction cost, year of completion, and capitalization structure). The 26^{th} unit is an energy-limited hydro unit, for which the inputs include, in addition to those noted above, the plant's capacity factor (equivalent to its maximum energy output for the year). This treatment of hydro as energy-limited ensures that hydro displaces the most expensive energy (i.e., at the top of the load-duration curves).

Figure 6.1 Example Load-Duration Curves for Peak and Off-Peak Seasons



The model dispatches these 26 generating units separately for the two seasons. Although the calculation process is the same for the two seasons, the results differ because of differences in the load-duration curves and because all the planned maintenance is assumed to occur in the off-peak season.

The plants are first dispatched against the load-duration curve on the basis of bid price, the default for which is variable (fuel plus variable O&M) costs. (If the user bids a zero price for a unit, the generator is treated as a must-run unit and is dispatched first by the model.) Because plants are not available 100% of the time, we also model forced outages on a probabilistic basis.[3] Thus, the higher-cost plants will see demands not only from customers, but "equivalent demands" based on the probability that plants lower in the dispatch order (i.e., less expensive) will be undergoing a forced outage. The model creates an equivalent load-duration curve for each plant, which extends the amount of time the plant runs based on the forced-outage rates of the plants lower in the dispatch order.

Model results include spot prices for each point on the two load-duration curves. These prices are based on the bid prices for each generator. The prices also reflect any externally imposed uplift charge, capacity charge, or emissions taxes. Finally, the prices during high-demand hours reflect generating-unit startup costs and the costs of unserved energy for those hours that unconstrained demand exceeds supply. See Appendix F for more details on the inputs and results from ORCED.

ORCED can be run iteratively to estimate the response of customers to changes in overall and time-of-use electricity prices. User inputs include an overall price elasticity of demand and a time-of-use elasticity. The overall price elasticity adjusts the entire load-duration curve up or down in response to decreases or increases in the average price of electricity. The time-of-use elasticity adjusts each point on the load-duration curve up or down based on price decreases or increases during that time period.

In addition, the model can use the time-of-use elasticity to compute the value of unserved energy (in ¢/kWh) that equilibrates supply and demand when unconstrained demand would otherwise exceed online supply. Alternatively, the user can input an estimate of the value of unserved energy, which is then used to calculate the costs associated with those times when unconstrained demand would exceed supply. A third approach involves user specification of a minimum reserve margin and associated annual capacity payment (in $/kW-year) to pay for this "extra" capacity.

In addition to dispatching power plants and computing production costs, the model can also "optimize" the mix of generating units available for the year of analysis. (That is, the model includes a capacity-expansion module as well as a production-costing module.) We put optimize in quotes because the factor on which to optimize is almost certain to be different for a competitive electricity industry than it was for the regulated electric utility industry. For example, the model could choose from among the following optimization functions:

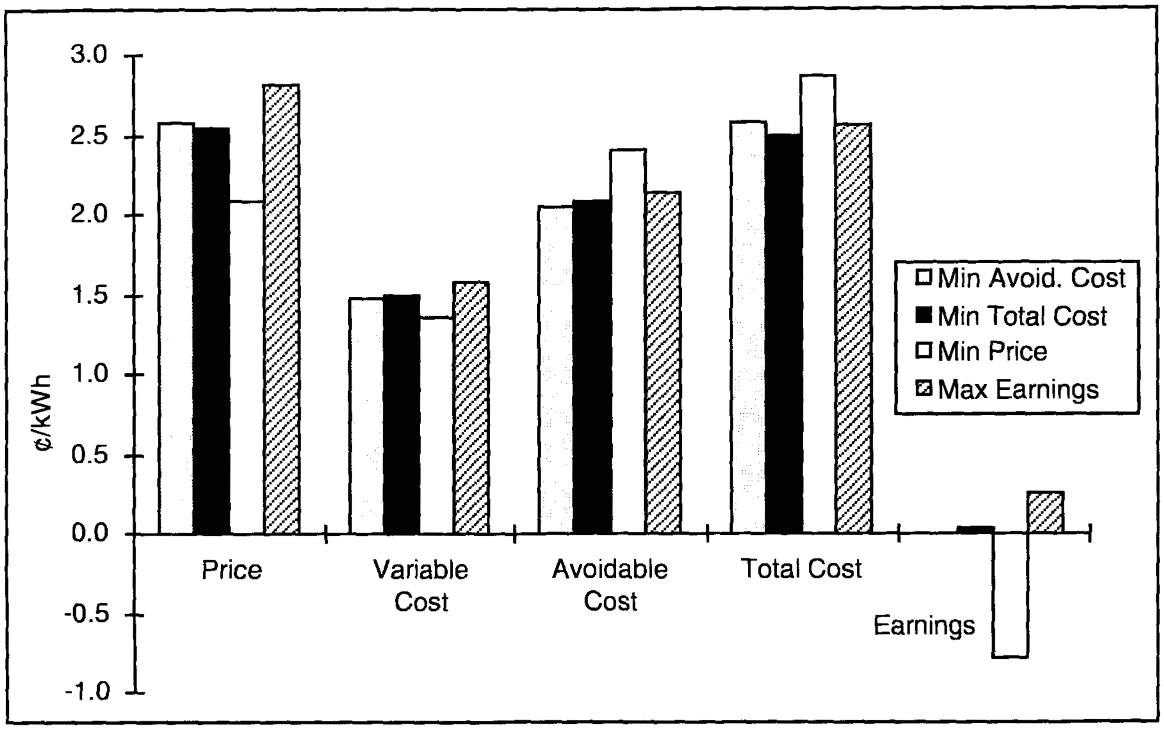
- Minimize total costs;
- Minimize avoidable costs (fuel, variable and fixed O&M);
- Minimize electricity prices; or
- Maximize generator earnings.

In Figure 6.2 we show the impact of different objective functions for optimization. Minimizing price does not necessarily minimize cost, because prices are based on the variable costs only and ignore fixed costs. Given choices of technology, ORCED would select low variable cost but high total cost technologies. Conversely, maximizing earnings does not raise total cost. Instead, the model selects high variable/low fixed cost technologies. For our analysis we chose to optimize on minimizing avoidable costs; we made this choice because it was conceptually the most appealing and the results were the most reasonable for a system-wide optimization. For plants not yet built, their capital costs as well as all operating costs are avoidable. Since no costs have been expended to build them, their construction costs are not "sunk" and can be avoided by not building them.

In addition to specifying the optimization function, the user can also specify constraints on individual generating units or the mix as a whole. For example, the user could set minimum and/or maximum capacity levels for each generator. Maximum levels could be specified for those units that were built earlier. Minimum levels could be specified for those units that must be available for policy reasons (e.g., renewable resources that might not be fully cost-effective but are deemed desirable from a broad societal perspective). Also, minimum levels for new plants may be specified to represent plants built between the current year and the study year. Otherwise, the model may choose not to build these intermediate plants, selecting only those with the most advanced technologies. Constraints could be specified for a minimum capacity reserve margin, for a maximum carbon emission allowance, or to ensure that each generating unit recovers at least its variable plus avoidable fixed costs, and so on.

Since ORCED is written in Microsoft Excel, there are several methods that can be used for optimization. The easiest is to use the built-in Solver tool. A single cell can be identified as the objective function to be minimized, and other cells can be identified as variables, with constraints placed on their values and/or other parameters within the spreadsheet. Since the problem is non-linear, Solver uses a Generalized Reduced Gradient method, running the model thousands of times searching for a solution. Another method, which is generally slower but avoids problems of local optima, is the use of genetic algorithms.

Figure 6.2 Generation Price and Costs Using Different Optimizations (10% Fixed Reserve Margin)



6.4 SCENARIOS FOR 2010

6.4.1 Calibration to EIA AEO97

Before analyzing the two end-use efficiency scenarios, we first calibrated ORCED results to those produced by EIA's NEMS model for 1995 and 2010. Unfortunately, reconciling the two sets of results to each other is difficult because of differences in the ways that the two modeling systems classify various costs (e.g., fuel, variable O&M, fixed O&M, and capital costs associated with generation) as well as EIA's inclusion of administrative and general (A&G) and customer service costs in the basic categories of generation, transmission, and distribution costs.[4] Because of these difficulties, our numbers do not always match the EIA numbers exactly.

This calibration ensures that the assumptions concerning the mix of generating units, fuel prices, customer demand, environmental regulations, and so on are consistent between ORCED and those developed by EIA. For example, both sets of results assume the continuation of current economic and environmental policies affecting the U.S. electricity industry. However, EPA's proposed regulations to tighten standards for emissions of nitrogen oxides and small particulate matter are reflected in neither the EIA nor the ORCED results.

We first developed a base case for the year 2010 that includes the same mix of generating units (in both capacity and energy) as that produced by EIA, with the same reserve margin (11%), as shown in Table 6.1. In addition to data from the AEO97, we used other data from EIA (EIA 1996b, EIA 1996c, EIA 1995), as well as data from the North American Electric Reliability Council (NERC 1996), the Electric Power Research Institute (EPRI 1993), and a compilation of various official databases by Resource Data International, Inc. (RDI 1996).

Table 6.1 Comparison of Year 2010 AEO97 and ORCED Estimates of U.S. Generating Capacity and Generation

	Percent of generating capacity		Percent of generation	
	EIA	ORCED	EIA	ORCED
Hydro+other renewables	13.4	11.3	9.6	9.2
Coal	35.0	36.9	50.1	50.8
Nuclear	10.2	11.1	15.8	15.5
Oil	3.2	3.1	1.5	0.1
Gas	38.3	37.6	23.0	24.4

ORCED analyzes the generation sector only; the model is silent with respect to the costs of transmission, distribution, and customer service. ORCED produces the following cost estimates for 2010, all expressed in 1995 dollars and adjusted upward by 1/0.93 to reflect the 7% T&D losses between the generator busbar and the customer meter:[5]

Fuel	1.35
Variable O&M	0.18
Fixed O&M	0.51
Capital	1.00
Total	3.04¢/kWh

We developed an estimate of the EIA capital cost of generation by subtracting estimates of the capital costs associated with transmission, distribution, and administrative and general (A&G) services from EIA's total capital cost:

$$[2.32 - (0.52 + 1.46) * 0.63 - 0.08] = 1.00¢/kWh.^{6}$$

Total (Trans + Dist) A&G

Our estimate of the EIA fuel cost is based on the sum of EIA's fuel cost plus 88% of its wholesale purchase cost:

$$(0.98 + 0.67*0.88) = 1.57¢/kWh.^{7}$$

Fuel Wholesale

We used the ORCED estimates of fixed and variable O&M costs to impute a comparable (i.e., equal) value for EIA.

The net result is very close agreement between the ORCED and EIA scenarios for 2010 (Table 6.2). EIA's estimate of the total cost of generation (3.26¢/kWh) is 7% higher than the ORCED result (3.04¢/kWh). The ORCED cost is lower because ORCED dispatches fewer expensive oil-fired resources than does the EIA model (Table 6.1). These differences in dispatch and variable costs occur because ORCED dispatches generation nationwide and ignores transmission constraints. The close agreement between EIA and ORCED results, in spite of all the adjustments required to produce a set of internally consistent and comparably defined terms, is reassuring. It lends confidence to our development of alternative cases in which we intended to reflect more fully than EIA did the effects of competition in bulk-power markets.

Table 6.2 Comparison of EIA and ORCED Estimates of Generation Costs (1995¢/kWh)

Generation costs	EIA AEO97	ORCED
Capital	1.00	0.99
Fuel	1.57	1.36
O&M	0.69	0.69
Total	3.26	3.04

6.4.2 The Base Case for a Competitive Market

Beginning with the AEO97 case, we developed a case intended to reflect the workings of a fully competitive bulk-power market in the year 2010. (The AEO assumes a continuation of current economic regulation, as indicated above, and therefore does not account for the possible effects of a restructured and largely competitive U.S. electricity industry.) To reflect these changes, we let the model select the amounts of each of the generating units that minimize the sum of variable plus avoidable costs. Instead of specifying the amount of generating capacity that must be online in 2010 (to yield a 10.7% reserve margin in the AEO97 case), we allowed the model to select the amount of capacity that minimized the cost of the power-supply system plus the cost of unserved energy. We used a demand elasticity of -0.05 for those time periods when capacity is insufficient to meet unconstrained demand. The resultant optimization yielded a reserve margin of 6.8%.

In general, we set prices equal to their real-time (hourly) values based on the variable (fuel plus variable O&M) cost of the unit on the margin each hour of the year, adjusted overall electricity demand to reflect lower prices using an assumed overall elasticity of -0.5, and adjusted the load shape to reflect the response to real-time pricing using a value of -0.1 for the price elasticity within each time period.

Beginning with the ORCED run that matches the AEO97 values for 2010, we first reran the model allowing it to select the "optimal" amounts of generating capacity from among all the plants that, according to EIA, are scheduled to come online after the year 1998. (The optimization was based on a minimization of avoidable costs.) We also allowed the model to select plants for retirement. For each of the new plants, we use the levelized fixed charges rate to calculate the annual capital cost of the plant and treat all fixed costs (both capital and O&M) as avoidable.

Next, we adjusted the load-duration curves for the two seasons simulated by the model (peak and off-peak). The new system load has a peak demand that is 3.4% below the AEO97 case and a total demand that is 1.2% higher. We then reran ORCED using the new load shapes. Table 6.3 compares the two sets of results. Although demand is higher in the restructuring case than in the AEO97 base case, carbon emissions are lower. The lower carbon emissions are the result of reduced coal use and increased natural gas use in the restructuring case.

Notice that, under restructuring, the total generating cost goes down 0.3¢/kWh and yet the system average price increases slightly. In a deregulated market, prices will be based on the variable cost (or bid price) of the most expensive plant at that time. This is known as the "market clearing price." Consequently, the link between total costs and prices is broken. Whereas current electric utility regulation sets prices to recover total costs, future prices may, or may not, be sufficient to recover all costs.

Overall, ORCED prices under restructuring did not differ greatly from the AEO97 price forecast. Part of the reason for this similarity of results is that EIA did assume some cost decreases in their model; we did not assume further O&M cost decreases on a plant-by-plant basis due to the pressure of competition. Also, the objective function used in our cases was to minimize avoidable costs on a system-wide basis. This did not necessarily create the lowest-priced scenario, as discussed in section 6.3. Because prices were similar to those in the AEO97 (less than 5% difference when factoring in transmission and distribution prices), we simply used the AEO97 price forecasts for analysis of energy-efficiency savings in the other chapters of this report.

Table 6.3 Comparison of Year 2010 Forecasts: AEO97 and the ORCED Base Case for a Competitive Electricity Industry

	AEO97	Competitive Industry Restructuring
Peak demand, GW	734	709
Total end-use electricity sales, TWh	3,784	3,828
System load factor, %	62.8	65.7
Reserve margin, %	10.7	6.8
Generation shares, %		
Coal	50.8	47.4
Gas	24.4	29.2
Other	24.8	23.4
Generation prices and costs, ¢/kWh		
Retail price	3.04	3.02
Variable cost	1.43	1.45
Total cost	2.81	2.51
Carbon emissions, MtC	631	625

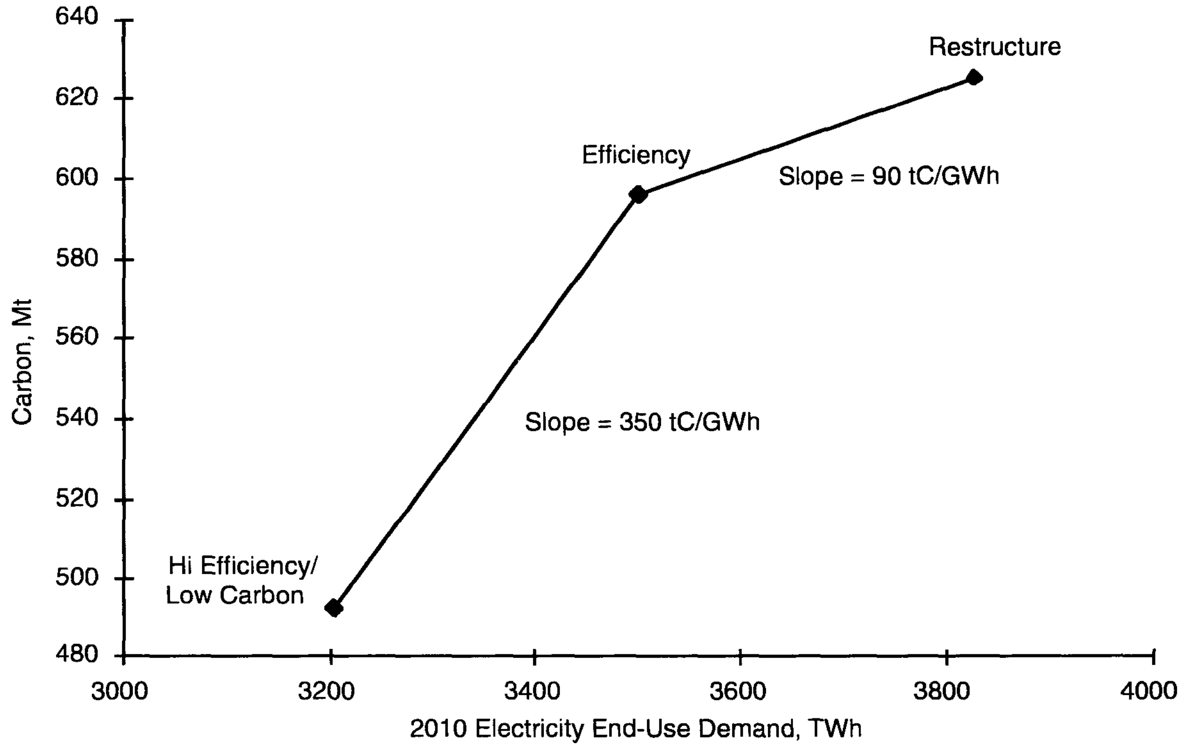
6.4.3 Efficiency and High-Efficiency/Low-Carbon Cases

We next applied the electricity-savings estimates, described in Chapter 3 for the residential and commercial sectors and in Chapter 4 for the industrial sector, to adjust the aggregate load shape for the United States as a whole. We then reran ORCED using the new, lower load shapes. As in the reference case, capacity was optimized to minimize avoided costs, and dispatched on the basis of lowest variable costs. Avoided costs for existing plants only included their variable, start-up, and fixed O&M costs, while plants to be built between 1997 and 2010 also included the annualized capital cost of their construction. As part of the high-efficiency/low-carbon case, we included an additional cost of $50 per tonne of carbon, to be consistent with the rationale used in the demand-side efficiency scenarios.

Once power plant production levels were determined, carbon production and primary energy use could be calculated. We calculated marginal carbon savings, the carbon saved by the reduction in energy, by taking the difference in carbon production and dividing by the reduction in energy demand. This is in contrast to using the average carbon intensity as an approximation of the carbon saved per unit of energy saved. The marginal carbon and energy savings take into account the change in production mix that occurs with energy- efficiency and carbon-reduction measures. A plot of the carbon savings and primary energy used in each scenario shows the changes as a function of the end-use energy saved (Figures 6.3 and 6.4). The slopes of the lines represent the marginal carbon and primary energy saved.

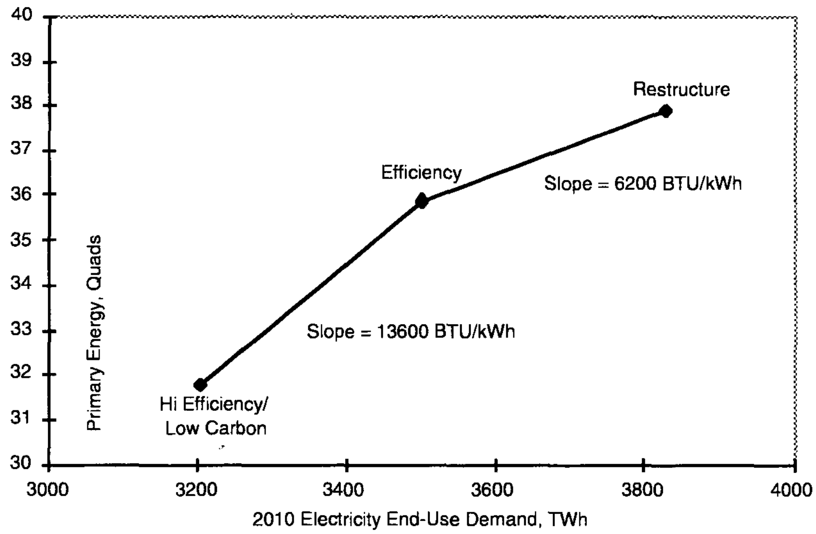
Table 6.4 summarizes the results for the three scenarios. Table 6.5 describes these results in terms of percent change relative to the base case for a competitive utility industry. The efficiency case yielded a 8.5% reduction in electricity end-use energy and the high-efficiency/low-carbon case reduced end-use energy by 16.3% relative to the restructuring case summarized in Table 6.3.

Figure 6.3 Carbon Production Versus End-Use Demand: Reductions Due to Energy Efficiency and Carbon Management



Note: Slope is equal to marginal carbon savings in tonnes of carbon per gigawatt-hour.

Figure 6.4 Primary Energy Production Versus End-Use Demand: Reductions Due to Energy Efficiency and Carbon Management



Note: Slope is equal to marginal energy savings in Btu per kilowatt-hour.

Table 6.4 Comparison of Year 2010 Forecasts: Results of Efficiency and High-Efficiency/Low-Carbon Scenarios

	Competitive Industry Optimization	Efficiency	High-Efficiency/ Low-Carbon
Peak demand, GW	709	651	596
Total Primary Energy used, quads	37.9	35.9	31.8
Total electricity generated, TWh	4,090	3,740	3,420
Total end-use electricity demand, TWh	3,830	3,500	3,200
System load factor, %	65.7	65.5	65.5
Reserve margin, %	6.8	7.9	12.9
Generation shares, %			
Coal	47.4	52.1	46.2
Gas	29.2	22.2	26.0
Other	23.4	25.7	27.8
Generation prices and costs, ¢/kWh			
Retail price	3.02	3.03	3.66
Variable cost	1.45	1.43	2.07
Total cost	2.51	2.46	3.21
Carbon emissions, MtC	625	596	492
Average carbon emissions, kg/MWh	163	170	154
Marginal carbon saved, kg/MWh	–	89	350

Table 6.5 Comparison of Year 2010 Forecasts: Effects of Efficiency and High-Efficiency/Low-Carbon Scenarios

	Change relative to the competitive utility industry base case	
	Efficiency	High Efficiency / Low Carbon
Peak demand	-8.2%	-16.0%
Total energy	-8.5%	-16.3%
System load factor	-0.2% points	-0.2% points
Reserve margin	+1.1% points	+6.1% points
Generation shares		
Coal	+4.7% points	-1.2% points
Gas	-7.0% points	-3.2% points
Other	+2.3% points	+4.4% points
Generation prices and costs		
Retail price	+1%	+21%
Variable cost	-1%	+43%
Total cost	-2%	+28%
Carbon emissions	-4.6%	-21.2%

The efficiency scenario forecasts a lower percentage reduction in carbon (4.6%) than in end-use energy (8.5%) (Figure 6.5). The difference occurs because lower end-use demands translate into less construction and operation of high-efficiency gas-fired combustion turbines and combined-cycle units (Figure 6.6). (Because of their high capital costs, ORCED selects only the minimum amounts of advanced coal and renewable technologies in the base restructuring case.) In the efficiency case, relative to the restructuring case, capacity and generation for combined-cycle units declines by about 27%; capacity for combustion turbines drops 28% (generation drops by 68%); and coal and gas-powered steam plants actually increase their production slightly.

Identification of high-efficiency gas-fired combustion turbines and combined-cycle units as the marginal plants under consideration has the effect of substantially lowering the avoided carbon from electric efficiency improvements. The forecasts contained in AEO97 are consistent with this assumption through the year 2010. For example, page 49 of the AEO97 states that, "of the new capacity [required through 2015], 81 percent is projected to be combined-cycle or combustion turbine technology fueled by natural gas or both oil and gas."

In contrast, the HE/LC case forecasts a higher percentage reduction in carbon (21.2%) than in end-use energy (16.3%). This is because the inclusion of the charge of $50 per tonne of carbon changes the mix of technologies used to produce electricity so that low-carbon supply options are favored. Over 16% of the coal capacity is retired in this scenario, and the remaining, more-efficient coal plants operate at a lower capacity factor. Overall, generation from coal declines 18% compared to the reference case. Capacity from combined cycle plants actually increases over the amount in the efficiency case, but still has a 14% decline from the reference case. Combustion turbine generation declines 84% from the reference case while combined cycle generation declines only 13%.

Figure 6.5 Energy and Carbon Changes from Restructure Case

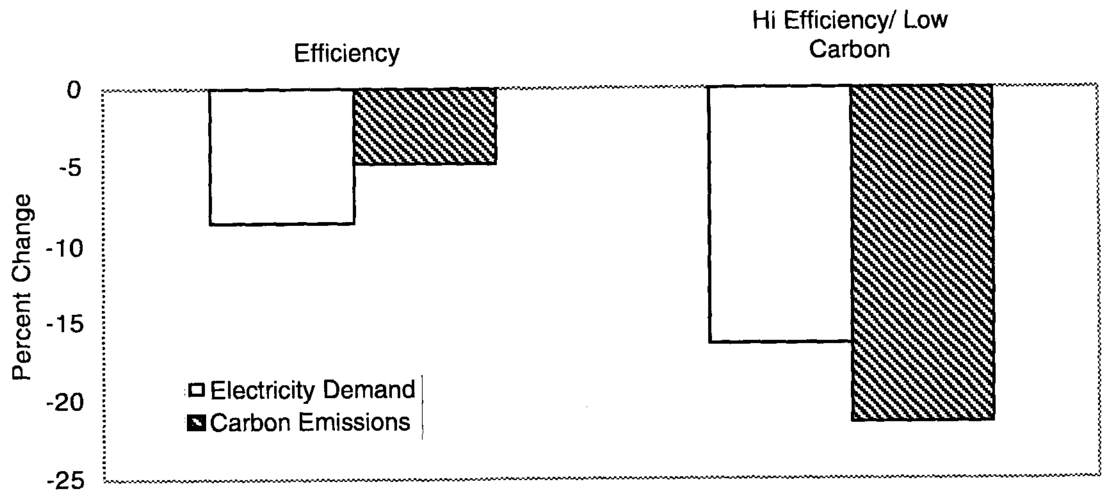
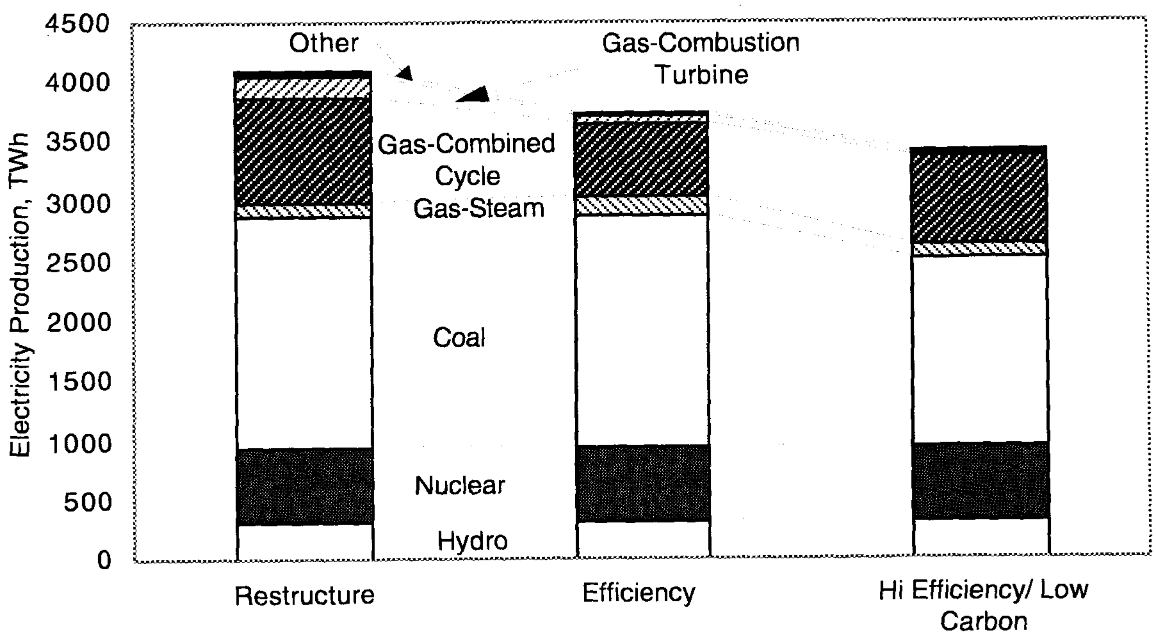


Figure 6.6 Generation by Technology Under Each Scenario



Compared to the reference case, generating prices and costs remain about the same under the efficiency scenario. In the HE/LC scenario, prices and costs increase about two-thirds of a cent because of the additional charge of $50/tonne of carbon. This carbon charge represents a 1.4¢/kWh increase to the more expensive coal plants, but only a 0.5¢/kWh increase to the better gas-fired combined cycle plants. ORCED redispatched and changed capacities so that the cost increase would be minimized. Note that, although the generation price increases by 21%, the price of generation represents only about half of the total price of electricity. Keeping transmission, distribution, and customer service prices the same, the total price increase would be only 10%.

Because electricity prices are essentially unchanged under the efficiency scenario (changing from only 6.20¢/kWh to 6.22¢/kWh including other components), total electricity costs to consumers decrease by an amount that is proportionate to the reduced electricity demand (i.e., 330 TWh). Thus, the cost reduction is approximately $20 billion. This value takes into account the savings in transmission, distribution, and customer service costs included in the full retail price of electricity. The high-efficiency/low-carbon case yields slightly lower savings of around $18 billion. Total energy savings almost double to 630 TWh, but the price increase of 0.65¢/kWh due to the carbon charge cuts into the overall savings.

One way to measure the cost impact of the $50/tonne of carbon cost is to evaluate the extra cost due to plant operation changes (redispatch, retirements, and new construction). In the high-efficiency/low-carbon case, we construct and operate the plants as optimized with the carbon charge. If we remove the charge, but construct and dispatch plants as in the high-efficiency/low-carbon case, we are no longer operating at minimum cost. The excess above the minimum cost is about $2.2 billion. Dividing this amount by the tons of carbon saved from the minimum-cost case yields an average cost of $30 per tonne of carbon saved.

Allocating the carbon savings in the efficiency case between the buildings and industrial sectors, we find that the buildings sector (residential and commercial) saved 19.4 Mt of carbon while the industrial sector saved 9.6 Mt (Table 6.6). The carbon savings for each were proportional to their savings in electricity, since electric generation is determined by the system load.

Table 6.6 Carbon Reductions from Electricity Savings by Sector under the Efficiency and High-Efficiency/Low-Carbon Cases (MtC)

Sector	Efficiency Case	High-Efficiency/Low-Carbon Case
Buildings (Residential)	10.9	49.2
Buildings (Commercial)	8.5	38.3
Industry	9.6	45.0
Total	29.0	132.5

Note: Transport is not included since electricity use in that sector is negligible.

Some of the 133 Mt of carbon that is forecast to be displaced by the high-efficiency/low-carbon case can be attributed to the end-use efficiency improvements in the buildings and industrial sectors. The remaining savings are attributed to the change in electricity generation mix that resulted from the charge of $50/tonne of carbon. Two methods of allocating the carbon savings between the end-use and supply sectors were examined.

- In the first method, ORCED modeled the high-efficiency/low-carbon case without the $50/tonne charge in the supply sector. The result was a savings of 56 MtC, attributed to energy efficiency alone. The rest of the carbon savings (77 MtC) is then attributed to the electricity sector.

- In the second method, ORCED modeled the restructure case with the $50/tonne charge in the supply sector, but without the demand reduction due to efficiency improvements. The result was a savings of 33 MtC, which is attributed to the electricity sector. The rest of the carbon savings (100 MtC) is attributed to the end-use sectors based on their energy savings.

The results of these alternative allocations (including the distribution of carbon savings across the buildings and industrial sectors) are shown in Table 6.7 and Figure 6.7. The total carbon that is displaced by the lower electricity demand is the same (133 MtC), but the allocation between the end-use and supply sectors varies widely depending on the method used to allocate the savings.

Because the savings involve a synergy between increased energy efficiency and changes to supply dispatching, it is difficult to identify the appropriate allocation of savings for the end-use vs. electricity supply sectors. To simplify matters, we used the average between the two methods described above. Specifically, the following averaging was used:

- The minimum carbon reduction attributed to electricity end-use efficiencies is 56 MtC (Method 1) and the maximum is 100 MtC (Method 2). The average of 78 MtC is therefore assumed for the end-use sector.

- The minimum carbon reduction attributed to the electricity sector is 33 MtC (Method 2) and the maximum is 77 MtC (Method 1). The average of 55 MtC is therefore assumed for the electricity supply sector.

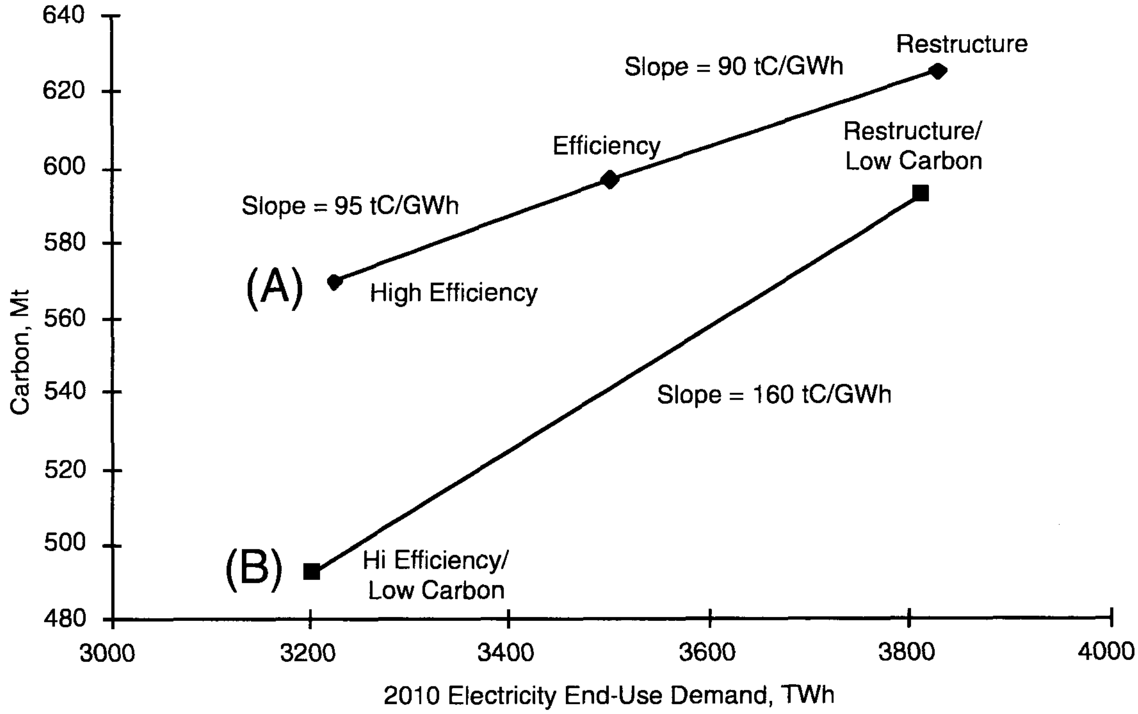
Table 6.7 summarizes this allocation process.

Table 6.7 Allocation of Carbon Reductions from the Electricity Saved by the High-Efficiency/Low-Carbon Case (MtC)

Sector	Method 1: Carbon Reduced by Energy Efficiency First	Method 2: Carbon Reduced by $50/tC Charge First	Final Allocation by Averaging
Buildings (Residential)	21	37	29
Buildings (Commercial)	16	29	22
Industry	19	34	27
Subtotal	56	100	78
Electricity Sector	77	33	55
Total	133	133	133

Based on the results shown in Figure 6.7, 160 tonnes of carbon are displaced for each GWh of electricity saved in the high-efficiency/low-carbon case with carbon permit price of $50/tonne, reflecting the introduction of new low-carbon technologies. This is the marginal carbon-to-energy ratio that is therefore used for analyzing the impacts of other carbon management strategies in the electricity sector in Chapter 7. This value is significantly higher than the marginal carbon-to-energy ratio used in the efficiency case (90 tonnes of carbon per GWh of electricity, as also shown in Figure 6.3), for the reasons noted earlier.

Figure 6.7 Carbon Reductions Due to Energy Efficiency and Carbon Management: (A) Without a Carbon Charge and (B) With a Carbon Charge of $50/Tonne



Note: Slope is equal to marginal carbon savings in tonnes of carbon per gigawatt-hour. In (A), the high-efficiency option represents all the assumptions of the high-efficiency/low-carbon scenario except that there is no charge for carbon.

6.5 SUMMARY

The U.S. electricity industry is undergoing massive change. Because the process is far from complete, it is even more difficult to make estimates about electricity production and use for the year 2010 than it would otherwise be. However, we developed a reasonable and internally consistent picture of electricity demand and supply for the year 2010 on the basis of EIA's AEO97 projection and additional simulations with the Oak Ridge Competitive Electricity Dispatch (ORCED) model.

ORCED was used to simulate the operation of the U.S. electric power supply system in 2010. We first calibrated our input data so that our results closely matched those produced by EIA for its *Annual Energy Outlook 1997*. We then developed a case for 2010 that is intended to reflect the ways in which a fully competitive industry might operate. Compared to the AEO97, these results suggest greater electricity use, lower peak demand, and a generation mix that includes more natural gas and less coal. Thus, although consumption is higher, carbon emissions are lower.

We then simulated the operation of this competitive electricity industry given the efficiency-induced reductions in electricity use in the residential, commercial, and industrial sectors as described in Chapters 3 and 4. The efficiency case reduced electricity demand by 9%, which led to a 5% reduction in carbon emissions. The high-efficiency/low-carbon case reduced electricity use by 16%, which led to a 21% reduction in carbon emissions.

6.6 REFERENCES

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ENDNOTES

[1] States will continue to oversee power-plant siting and environmental emissions.

[2] The value of unserved energy is the price that customers would be willing to pay for electricity that is unavailable as a result of demand exceeding supply.

[3] The amount of computer time required for a full simulation depends strongly on the number of generators treated probabilistically. We found a reasonable tradeoff between computing time and accuracy when about 10 plants are modeled probabilistically and the other 16 are derated.

[4] Inclusion or exclusion of the data for cogenerators (which account for about 4% of electricity in the year 2010) is another source of confusion.

[5] According to AEO97, total generation in 1995 was 3246 billion kWh and sales totaled 3008 billion kWh, implying a loss of 7.3%.

[6] The 63% multiplier for T&D represents the percentage of T&D costs attributable to capital as opposed to O&M.

[7] This 88% multiplier is derived from ORCED's estimates of fuel and O&M costs of 1.35¢/kWh for fuel and 0.18 ¢/kWh for O&M. The 88% then is [=1.35/(1.35+0.18)].

Chapter 7

ELECTRICITY SUPPLY TECHNOLOGIES

7.1 INTRODUCTION

The electricity industry has many supply-side options at its disposal to reduce or offset carbon dioxide emissions from electricity production by the year 2010. One of these options, reconfiguring the generation mix to reflect a $50/tonne charge for carbon, was discussed in Chapter 6. We labeled this option "carbon-ordered dispatching" because it involves the same technologies that were considered in the AEO97 reference case. Electricity was redispatched from the existing generation mix, and the construction and retirement of power plants also changed, but no new technologies were introduced. Chapter 7 considers other electricity supply technology options, including:

- Repowering coal-based power plants with natural gas;
- Implementing renewable electricity technologies;
- Improving efficiency in generation and transmission and distribution (T&D) systems;
- Extending the life of existing nuclear plants; and
- Constructing new power plants using advanced coal technologies.

Each of these options is assessed independently. Because interactions among the options are not taken into account, there is a likely possibility of double-counting with respect to the actual emissions reduction potential.

The viability and costs of these supply options in 2010 are based on the assumption that the electricity grid is transformed by the carbon-ordered dispatching that occurs under the "high-efficiency/low-carbon" (HE/LC) scenario, as described in Chapter 6. Thus, since we assume that considerable decarbonization has already taken place, this chapter addresses the question: What additional supply technology options now make sense in a scenario in which carbon has acquired a value of $50/tonne? We conclude by discussing the significant contribution that renewable energy technologies can make by the year 2020.

7.2 REPOWERING COAL-BASED POWER PLANTS WITH NATURAL GAS

The conversion of existing coal-fired power plants to operate on natural gas (via repowering) is one option to significantly increase the efficiency of power generation and reduce carbon emissions in the U.S. electric power sector.[1] Natural gas is a less carbon-intensive fuel and its use also reduces emissions of the following criteria air pollutants: sulfur dioxide (SO_2), nitrogen oxide (NO_x), total suspended particulates (TSP), and hazardous air pollutants (HAPs). Our analysis shows that natural gas combined cycle (NGCC) is a cost-effective power generation technology and carbon emission reduction option. Depending upon assumptions regarding the differential in the delivered price between natural gas and coal, the price of carbon permits, and environmental externality values for criteria air pollutants, we found that carbon emissions of up to 238 MtC could be reduced annually through repowering.

7.2.1 Repowering Approachs

The simplest repowering approach is *site repowering*, where the existing power plant site is reused with an entirely new NGCC system. Cost and performance data for the General Electric "H" frame turbine was used; this class of turbine will be the most efficient in the post-2000 period, with the lowest cost per kilowatt of capacity. While site repowering provides the highest cycle efficiency (since none of the existing boiler island equipment is reused), it also requires a greater capital investment (see Appendix G-1).

The more conventional approach is referred to as *steam turbine repowering*. In this case, a new gas turbine and heat recovery steam generator (HRSG) are integrated with the existing steam turbine and auxiliary equipment from the coal plant. Due to age of equipment and the fact that the steam turbine was designed for linkage with a coal-fired boiler, the efficiency of a *repowered* steam turbine plant would be lower than at a *site repowered* plant. The steam turbine repowering option has a higher operating cost (due to the lower efficiency) but a lower capital cost (see Appendix G-1).

The cost-effectiveness ($/tC) of both repowering options was examined for all coal-fired power plants greater than 50 megawatts (MW).[2] Included in the cost calculation were the cost of repowering, hook-up, and transmission. We analyzed the site repowering results for the two alternative gas/coal price differentials: $0.72 and $1.18 per million Btu (MBtu)[3], three price ranges for carbon permits (<$50/tonne, $50-100/tonne, and $101-150/tonne), and three environmental externality values for SO_2 and NO_x (none, low, and high). In addition, a sensitivity analysis was performed to examine the impact on cost-effectiveness if additional natural gas pipeline infrastructure (hook-up and transmission) were not needed to ensure gas deliverability to repowered plants. This sensitivity analysis (referred to as the "no additional transmission cost" case) was conducted only for those power plants that are currently connected to the natural gas pipeline network (i.e., dual-fuel). Appendix G-3 contains a complete description of the methodological steps and key data parameters.

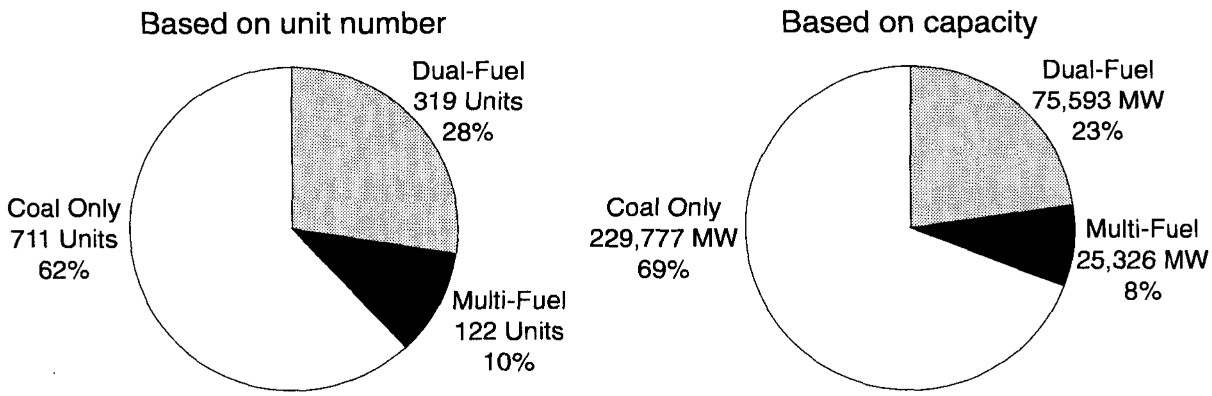
The analytical approach was static in that the cost of repowering was computed for each candidate power plant but the analysis did not optimize unit/plant production cost, dispatch, or system load. Moreover, for the steam repowering case, the largest steam turbine (not each individual steam turbine) at the plant was repowered to generate the equivalent of 1995 plant output (kilowatt-hours, kWh), since this is both more economic and consistent with industry practice than repowering each turbine. Lastly, the gas delivery infrastructure costs (hook-up and transmission) were derived assuming (1) no excess capacity in the current delivery system, and (2) that if such a fuel-switching strategy were implemented, the natural gas pipeline industry would build capacity (even if done incrementally) to meet the total estimated gas requirements of repowering all candidate plants and allocate appropriate delivery costs to each repowered plant. Assumptions regarding gas deliverability are described below in Section 7.2.2.2.

7.2.2 Repowering Issues

In 1995, there was 335 GW of coal-fired capacity at 404 power plants in the United States. Figure 7.1 indicates that this capacity was comprised of:

- 319 dual-fuel units (units that can burn both coal and natural gas),
- 122 multi-fuel units (coal-fired units at sites with natural gas or petroleum units), and
- 711 coal-fired units (units at coal-only plant sites).

Figure 7.1 Candidate Coal-Fired Power Plants for NGCC Repowering



These categories reflect differences in the investment cost of conversion and deliverability of natural gas (i.e., those plant sites consuming gas in 1995 would have a natural gas pipeline connection, thereby resulting in a lower hookup cost.)

7.2.2.1 Increase in Natural Gas Demand

Utility gas consumption in 1995 was 3.5 trillion cubic feet (TCF). Figures 7.2 and 7.3 show the increases in natural gas demand from this base that would result from either site or steam turbine repowering for each of three cost-effectiveness values: less than \$50/tC, \$50-100/tC, and greater than \$150/tC. The increase in gas demand ranges from 1.0 TCF (<\$50/tC) to 4.9 TCF (\$50-100/tC) in the low gas/coal price differential case without externalities. This quantity of gas for repowered plants represents 29% and 140% increases in 1995 utility gas consumption, respectively.

If all the candidate coal-fired power plants were repowered with NGCC, natural gas demand in the utility sector would increase by 9.0 TCF/yr (site repowering) or 9.4 TCF/yr (steam turbine repowering) to either 12.5 TCF/yr or 12.9 TCF/yr, respectively, an increase of over 250% compared to current consumption levels.

The potential gas price increase resulting from NGCC repowered plants was not analyzed in this study. Only the current and projected gas/coal price differentials expected under AEO97 were included in the cost analysis. However, EIA has prepared a preliminary estimate; they found that an 11 TCF increase in demand would increase natural gas prices by \$3.09/MBtu over 20 years (1995-2015), if coal-fired power plants were converted to natural gas when scheduled for life extension/refurbishment and there was considerable demand-side energy-efficiency investment.

Figure 7.2 Incremental Increase in Gas Consumption Resulting from Coal to Gas Conversion with Constant 1995 Gas/Coal Price Differential ($0.72/MBtu

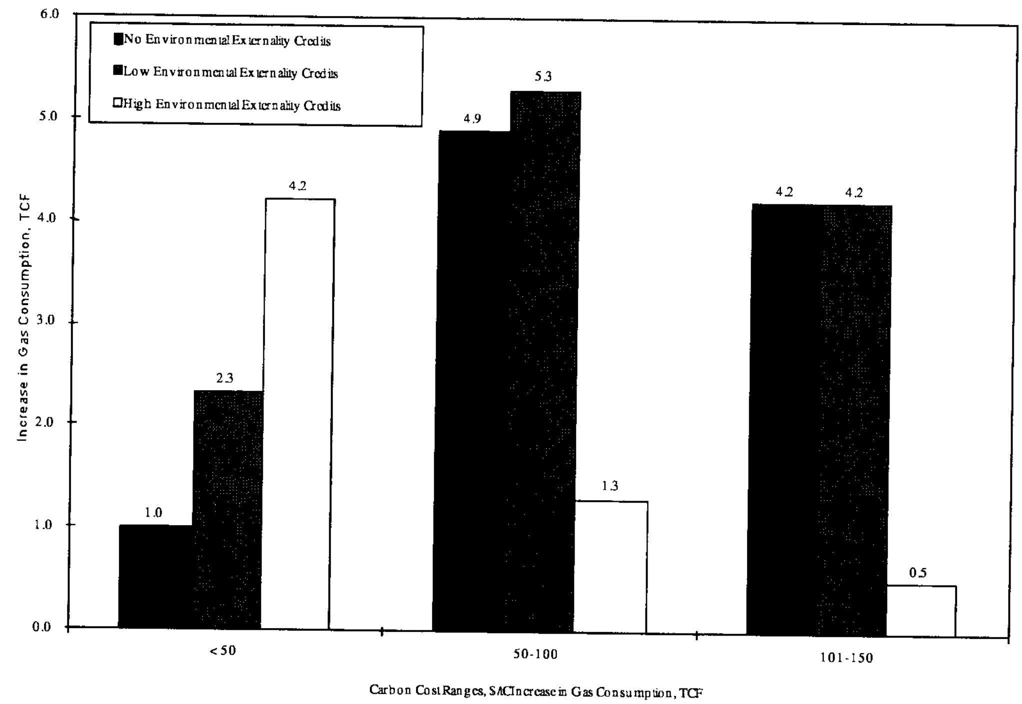
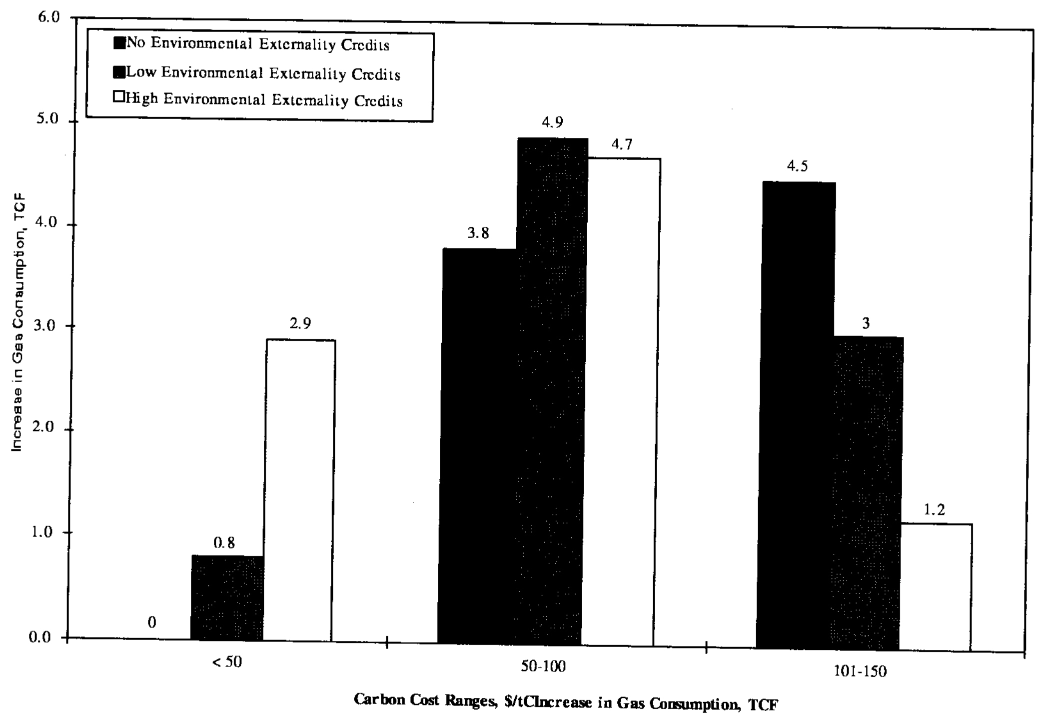


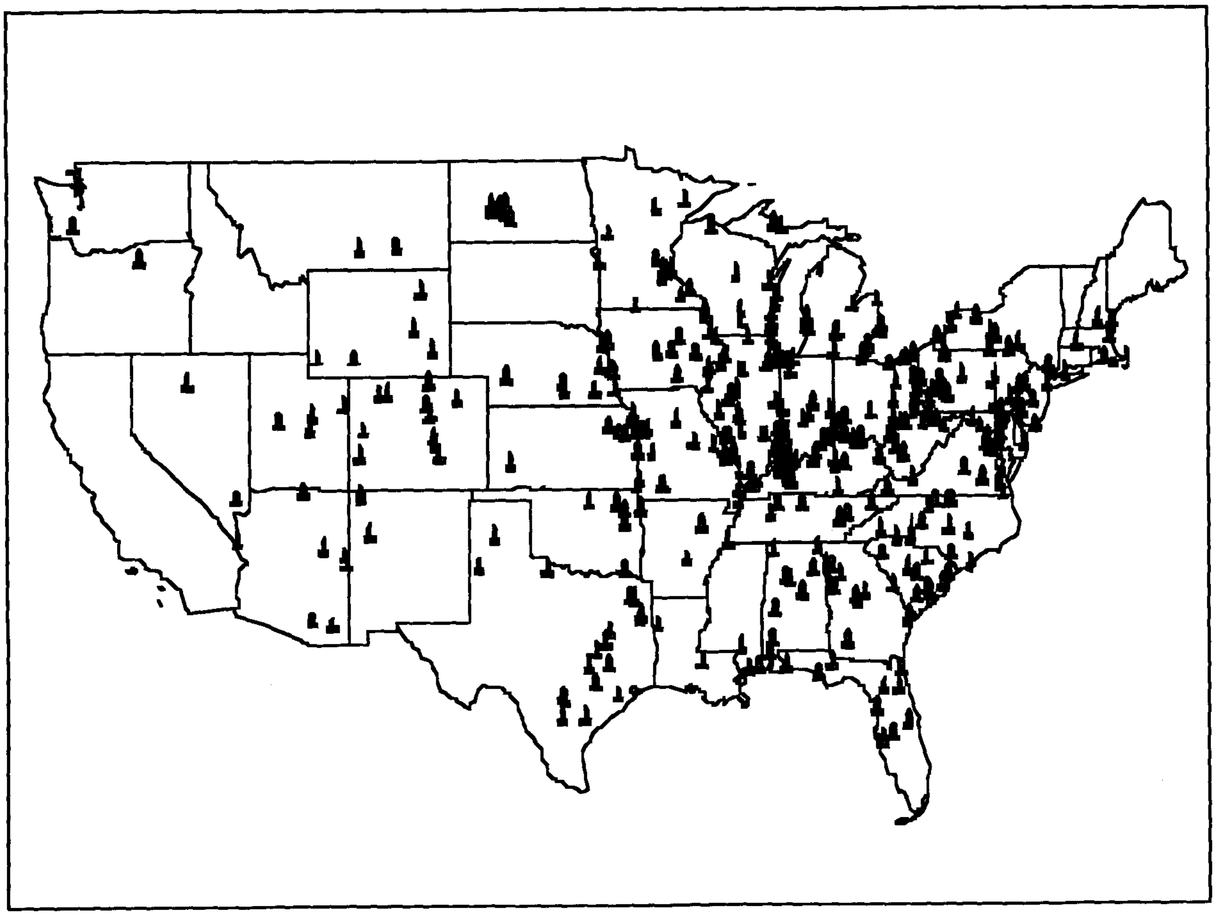
Figure 7.3 Incremental Increase in Gas Consumption Resulting from Coal to Gas Conversion with Constant 2010 Gas/Coal Price Differential ($1.18/MBtu)



7.2.2.2 Gas Deliverability

The spatial distribution of the initial 404 candidate plants is depicted in Figure 7.4. Some of the candidate plants were not considered for repowering since they were (1) not considered economic by EIA, or (2) determined to be unnecessary due to reductions in demand arising from end-use efficiency improvements.[2] Most of the plants are located in the Mid-Atlantic, South Atlantic, Midwest, and Plains regions. While these are also primary gas-consuming regions served by major trunk lines, many industry experts believe there is limited unused or underutilized capacity in the current 1.2 million mile pipeline system (transmission – 264,900 miles; distribution – 935,000 miles; field – 62,200 miles). Since this capacity is necessary to accommodate peak winter demand and non-utility growth, it is of little value to power plants considering conversion, since these power plants require firm pipeline commitments.

Figure 7.4 Location of Candidate Plants for Coal/Gas Repowering in the U.S.



Due to the potentially significant increase in utility gas demand that could result from repowering (either site or steam turbine) coal-fired power plants, and the uncertainties regarding when repowering would take place, new pipeline capacity sufficient to serve all candidate plants was developed to ensure deliverability. A detailed assessment was performed (using a geographical information system, GIS) to compute the distance of each candidate power plant to its nearest trunk line. Cost estimates were derived for the cost of upgrading the lines to meet the increased gas demands (see Appendix G-4).[4] Table 7.1 summarizes the distance of the candidate plants to their closest production zone.

The requirement to add new pipeline capacity could affect the attractiveness of repowering as a carbon mitigation strategy. During 1994 and 1995, 1,200 to 1,500 miles of new pipeline were added to the system. According to Federal Energy Regulatory Commission (FERC) filings of pipeline projects, there are a considerable number of new pipelines and pipeline expansions that have been proposed, some of which are still pending approval. While mileage is not included with each filing, in the regions of concern (Central, Midwest, Northeast, and Southeast), more than 8,200 miles of pipe is projected to be added; this level of expansion is greater than the 1994-95 rate of addition. However, it is not known how long it will take to complete these proposed pipelines. Consequently, an accurate assessment of the ability to increase the rate of pipeline expansion/construction could not be estimated as a part of this study.

Table 7.1 Plant Distance from Production Zone

Range	Dual-Fuel		Multi-Fuel		Coal Only		Total	
(Miles)	# Units	%	# Units	%	# Units	%	# Units	%
60 - 440	48	37	5	12	55	22	108	26
440 - 620	33	25	8	19	64	26	105	25
620 - 890	30	23	15	35	59	24	104	25
890-1,480	19	15	15	35	67	27	101	24
Total	130	100	43	100	245	100	418	100

7.2.3 Emissions Reductions

Based on our analysis, repowering of coal-fired power plants with NGCC is a cost-effective carbon reduction strategy. Tables 7.2-7.4 summarize the site repowering results for the two alternative gas/coal price differentials: \$0.72 and \$1.18 per million Btu (MBtu), three price ranges for carbon permits (<\$50/tonne, \$50-100/tonne, and \$101-150/tonne), and three environmental externality values for SO_2 and NO_x (none, low, and high). The price differential of \$0.72/MBtu represents the 1995 gas/coal price differential held constant, while \$1.18/MBtu is EIA's forecasted price differential for the year 2010.[5,6] In addition to the "no externalities" case, two alternative market values were used for SO_2 and NO_x: low externalities represent \$0 per ton of SO_2 and \$700 per ton of NO_x; high externalities represent \$100 per ton of SO_2 and \$1400 per ton of NO_x.

As can be seen in Table 7.2, given a carbon permit price of less than \$50/tC and a gas/coal price differential of \$0.72/MBtu, 30 to 119 MtC could be removed via NGCC site repowering, depending upon externality assumptions. When the price differential increases to \$1.18/MBtu, 0 to 83 MtC could be removed from utility emissions. Consequently, we see that a increase of \$0.46/MBtu in the price differential decreases carbon reductions from NGCC repowering by approximately 30 MtC. Although the disaggregated data are not presented, most of the carbon reduction in the <\$50/tC range actually occurs in the \$25-50/tC range.

An ancillary benefit of switching from coal to gas and improving conversion efficiency is reduction in SO_2 and NO_x,two criteria pollutants. At the <\$50/tC level, approximately 50% of the SO_2 and NO_x would be removed (depending on the externality value); at \$50-100/tC and higher almost all the remaining coal-fired SO_2 and NO_x emissions would be eliminated. If all the candidate plants were repowered, almost all of the SO_2 and most of the NO_x would be removed.

The economic value of the SO_2 and NO_x emissions reductions that would result from repowering of the plants was also assessed in this study. Using the methodology described in Appendix G-2, SO_2 was valued from $0-100/ton; NO_x was valued at from $700-1400/ton. These values were used as the basis for the environmental externality credits to offset the investment cost of repowering.

Table 7.2 Summary Statistics: Coal to Gas Repowering with a Carbon Permit Price of <$50/tonne

Externality Cases*	Incremental Carbon Removed (MtC)	Incremental SO_2 Removed (Mt)	Incremental NO_x Removed (Mt)	Affected GW	Gas Consumed (TCF)**
Constant 1995 Gas/Coal Price Differential ($0.72/MBtu)					
None	30.3	0.5	0.7	26.8	1.0
Low	66.0	1.2	1.4	63.3	2.3
High	118.6	4.0	2.6	122.6	4.2
Gas/Coal Price Differential in 2010 ($1.18/MBtu)					
Externality Cases*	Incremental Carbon Removed (MtC)	Incremental SO_2 Removed (Mt)	Incremental NO_x Removed (Mt)	Affected GW	Gas Consumed (TCF)**
None	0	0	0	0	0
Low	23.6	0.3	0.6	20.2	0.8
High	83.4	2.5	1.9	83.3	2.9

* Two alternative market values were used for SO_2 and No_x: low externalities represent $0 per ton of SO_2 and $700 per ton of NO_x; high externalities represent $100 per ton of SO_2 and $1400 per ton of NO_x.

**TCF = trillion cubic feet

Table 7.3 Summary Statistics: Coal to Gas Repowering with a Carbon Permit Price of $50-100/tonne

Externality Cases*	Incremental Carbon Removed (MtC)	Incremental SO_2 Removed (Mt)	Incremental NO_x Removed (Mt)	Affected GW	Gas Consumed (TCF)**
Constant 1995 Gas/Coal Price Differential ($0.72/MBtu)					
None	134.6	4.9	2.7	147.3	4.9
Low	140.4	6.7	2.8	165.6	5.3
High	106.7	5.0	1.8	130.8	4.2
Gas/Coal Price Differential in 2010 ($1.18/MBtu)					
Externality Cases*	Incremental Carbon Removed (MtC)	Incremental SO_2 Removed (Mt)	Incremental NO_x Removed (Mt)	Affected GW	Gas Consumed (TCF)**
None	109.6	2.5	2.2	108.9	3.8
Low	134.1	5.0	2.7	146.4	4.9
High	123.9	5.5	2.3	147.6	4.7

* Two alternative market values were used for SO_2 and No_x: low externalities represent $0 per ton of SO_2 and $700 per ton of NO_x; high externalities represent $100 per ton of SO_2 and $1400 per ton of NO_x.

**TCF = trillion cubic feet

Table 7.4 Summary Statistics: Coal to Gas Repowering with a Carbon Permit Price of $101-150/tonne

Constant 1995 Gas/Coal Price Differential ($0.72/MBtu)					
Externality Cases*	Incremental Carbon Removed (MtC)	Incremental SO_2 Removed (Mt)	Incremental NO_x Removed (Mt)	Affected GW	Gas Consumed (TCF)**
None	69.4	4.0	1.2	93.9	2.8
Low	31.0	1.6	0.5	43.8	1.3
High	13.1	0.6	0.2	20.9	0.5
Gas/Coal Price Differential in 2010 ($1.18/MBtu)					
Externality Cases*	Incremental Carbon Removed (MtC)	Incremental SO_2 Removed (Mt)	Incremental NO_x Removed (Mt)	Affected GW	Gas Consumed (TCF)**
None	117.2	6.6	2.3	148.4	4.5
Low	75.1	4.0	1.2	98.6	3.0
High	29.8	1.5	0.4	41.4	1.2

* Two alternative market values were used for SO_2 and No_x: low externalities represent $0 per ton of SO_2 and $700 per ton of NO_x; high externalities represent $100 per ton of SO_2 and $1400 per ton of NO_x.

**TCF = trillion cubic feet

7.2.4 Cost-Effectiveness

Figure 7.5 portrays the cost-effectiveness of site repowering with NGCC and the corresponding cumulative carbon removed for the two alternative gas/coal price differentials when no environmental externalities are considered. With a price differential of $0.72/MBtu, approximately 30 MtC can be removed for <$50/tC, an additional 135 MtC can be removed for $51-100/tC, and an additional 77 MtC can be removed for >$100/tC. When the price differential increases to $1.18/MBtu, 0 MtC of carbon are removed at <$50/tC, 110 MtC are removed at $51-100/tC, and an additional 132 MtC are removed at >$100/tC.

Figures 7.6 and 7.7 depict the effect of environmental externality credits for SO_2 and NO_x on carbon cost-effectiveness. As mentioned above, in addition to the "no externalities" case, two alternative market values were used for SO_2 and NO_x: low externalities represent $0 per ton of SO_2 and $700 per ton of NO_x; high externalities represent $100 per ton of SO_2 and $1400 per ton of NO_x. The rationale for these values is explained in Appendix G-3. Both Figures 7.6 and 7.7 (together with Tables 7.2 - 7.4) illustrate that the effect of the environmental externality credit is to shift the carbon cost curve downward and to the right causing more capacity (GW) and carbon removal (MtC) to occur at lower carbon permit price levels.

Because dual-fuel plants are already receiving natural gas (although at lower volumes than a repowered plant), a sensitivity analysis was conducted wherein no hook-up or transmission costs were incurred to deliver an increased quantity of natural gas to these repowered plant sites. This "no additional transmission cost case" is illustrated in Figures 7.8 and 7.9, which depict the two alternative gas/coal price differentials and include externality credits for site and steam turbine repowering. Since transportation costs comprise approximately 30% of the total investment cost, the carbon cost curves shift downward considerably when these costs are removed. In Figure 7.8, approximately 45 GW of coal-fired capacity can be repowered at <$50/tC, removing 42 MtC of carbon, 1.2 Mt of SO_2 and 0.9 Mt of NO_x. The amount of natural gas required by these repowered plants is 1.5 thousand cubic feet; approximately 50% of 1995 utility consumption.

The cost-effectiveness numbers derived in this study are optimistic. These numbers should be used with caution because they do not (or do not adequately) consider the following factors that will determine the ultimate cost-effectiveness of the coal-to-gas repowering:

- Potential increase in gas prices from NGCC repowering,
- Actual cost of repowering the candidate coal-fired power plants,
- Excess transmission capacity, and/or economies of scale in delivering the required gas,
- Capacity utilization of the converted plants,
- Costs associated with breaking long-term coal contracts, and
- Other socioeconomic factors (e.g., differential state/federal tax effects, displaced coal miners).

In addition, the effectiveness of repowering as a carbon control strategy will depend on whether and to what extent the converted plants are dispatched. If, because of the costs associated with conversion, the repowered plants are not dispatched or their utilization is minimized, the associated carbon reductions will depend on the fuels and technologies used at the plants dispatched ahead of the repowered plants.

Figure 7.5 Carbon Curve for Coal/Gas Site Repowering: No Environmental Externality Credits

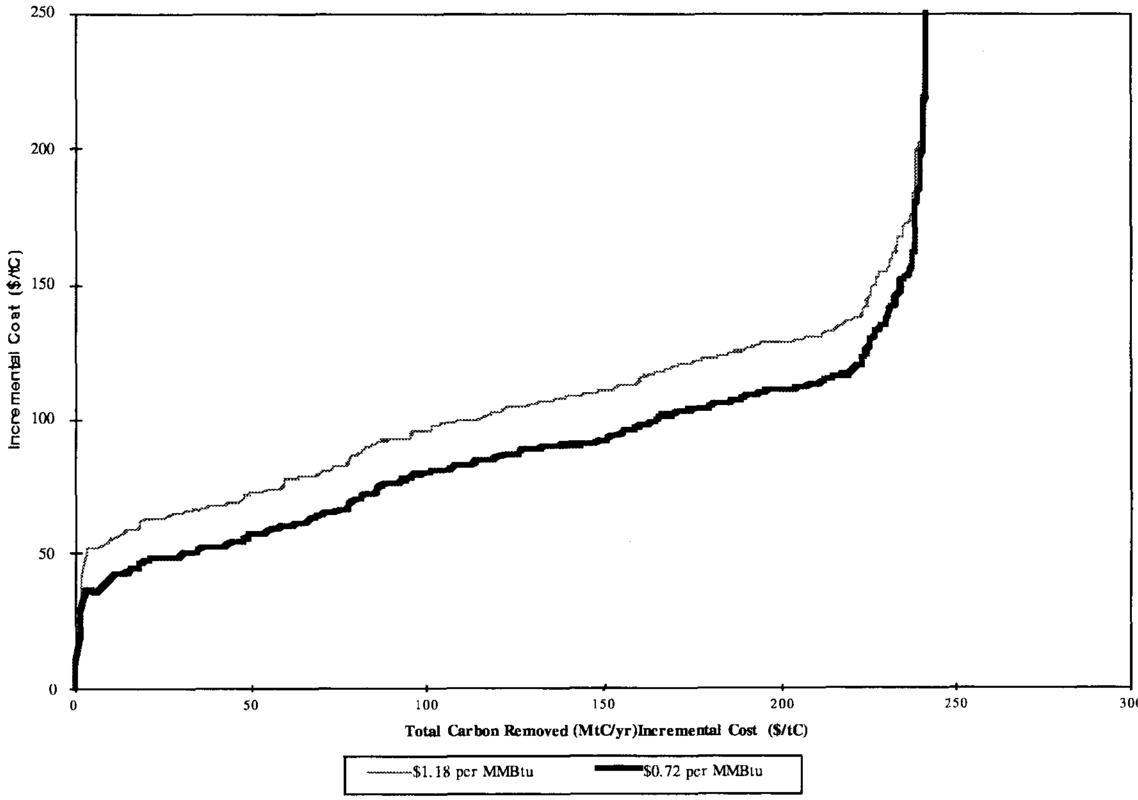


Figure 7.6 Carbon Curve for Coal to Gas Site Repowering: Effect of Environmental Externality Credits on Cost of Carbon Removal with Constant 1995 Gas/Coal Price Differential ($0.72 MBtu)

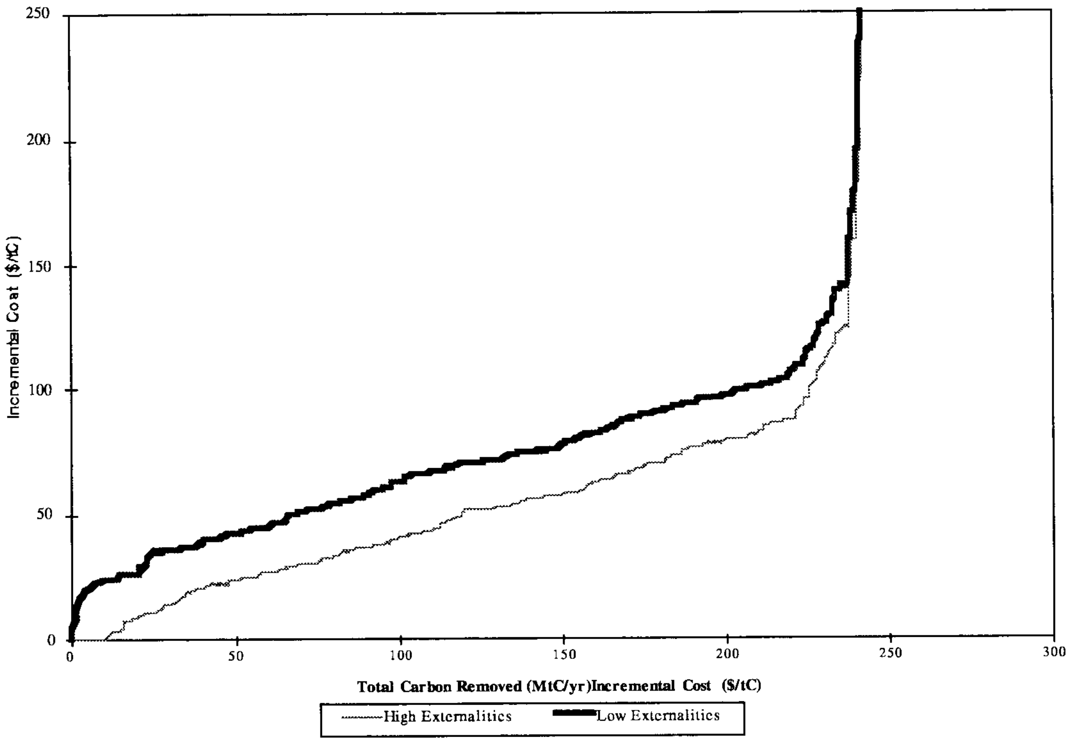


Figure 7.7 Carbon Curve for Coal to Gas Site Repowering: Effect of Environmental Externality Credits on Cost of Carbon Removal with Gas/Coal Price Differential in 2010 ($1.18 MBtu)

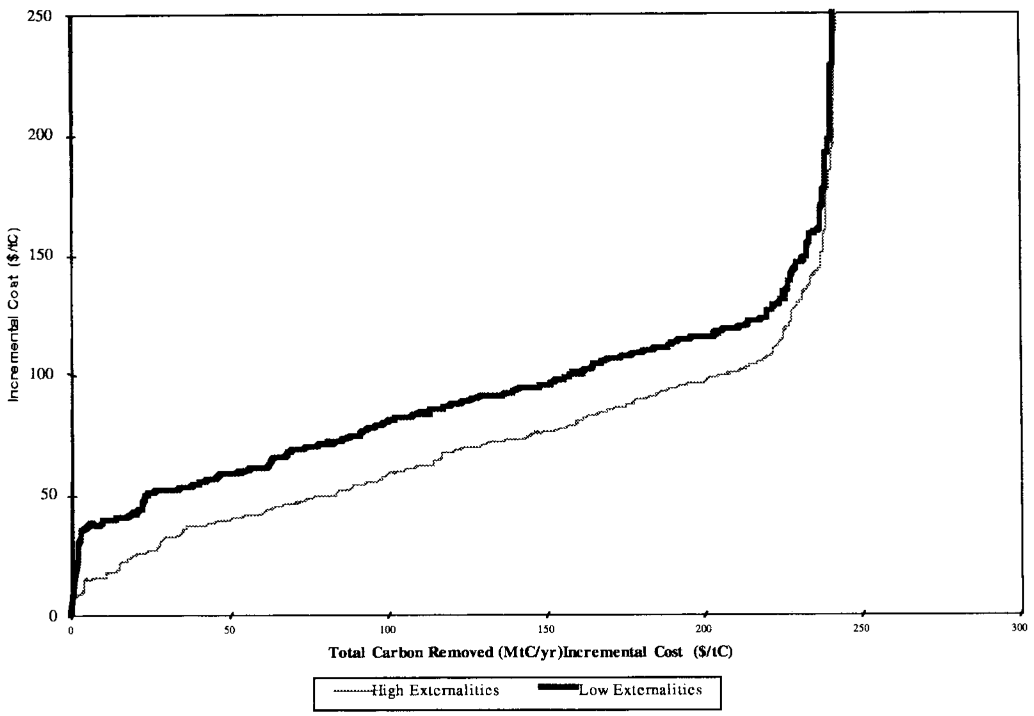


Figure 7.8 Carbon Curve for Partial Repowering[7]: Constant 1995 Gas/Coal Price Differential ($0.72 MBtu) Low Environmental Externality Credits

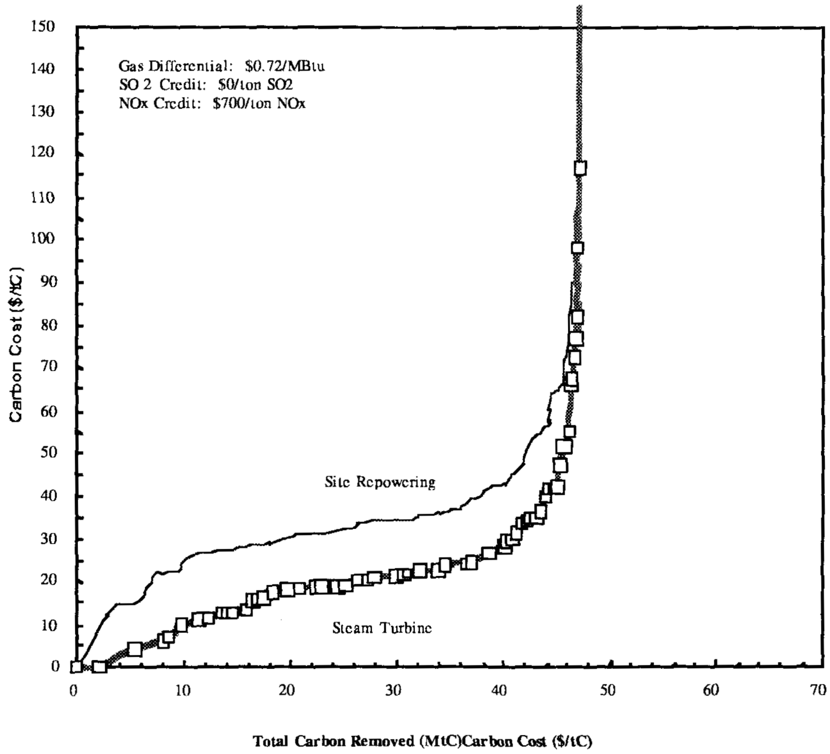
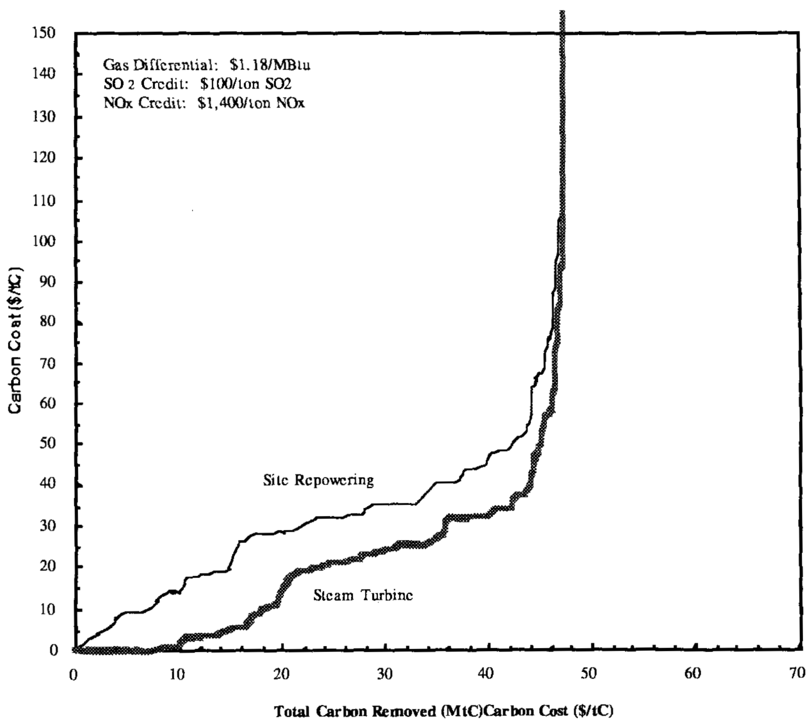


Figure 7.9 Carbon Curve for Partial Repowering[7]: Constant 2010 Gas/CoalPrice Differential ($1.18 MBtu) High Environmental Externality Credits



7.3 RENEWABLE ELECTRICITY TECHNOLOGIES

Over the long term, renewable energy technologies are likely to play a crucial role in limiting carbon emissions and global warming. While aggressive energy efficiency and fuel switching can reduce domestic carbon emissions to approximately 1990 levels by 2010, controlling or reducing carbon emissions beyond that date will require greater energy contributions from low-carbon technologies such as renewables. In other words, renewables will play an essential role in helping the United States to cut carbon emissions in the years beyond 2010.

Renewables will also make important contributions to both domestic and international carbon emission controls by 2010. Renewable technology contributions to domestic electricity and carbon savings in 2010 under the HE/LC scenario are summarized in Table 7.5.

Table 7.5 Additions to Generating Capacity Electricity and Carbon Emission Reductions from Renewables for the HE/LC Case in 2010

Renewable Technology	Capacity Additions (GW)	Electricity (TWh)	Carbon Emission Reduction (MtC)[a]
Included in Scenario:			
Biomass Cofiring	8-12	58-88	16-24
Wind	8-23	28-81	6-20
Hydropower	10-16	23-35	3-5
Subtotal			25-49
Excluded from Scenario:			
Landfill Gas[b]	3-7	20-50	25-53
PV	3-5	6-10	1-2
Geothermal	6-14	47-110	6-16
Solar Thermal	0-2	0-6	0-1
Subtotal			32-72
Total	38-79	182-380	57-121

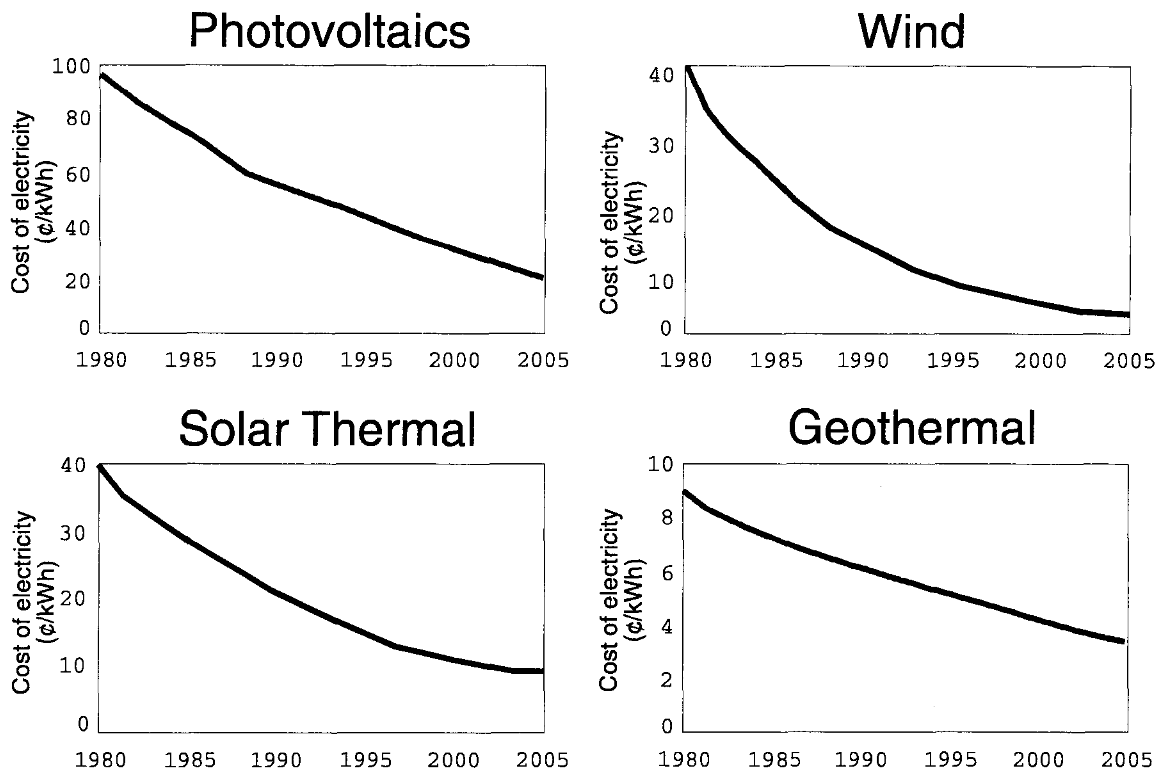
[a] These carbon emissions reductions represent the difference between the high-efficiency/low-carbon case and the business-as-usual forecast for 2010.

[b] The carbon emission reduction in this case represents the equivalent derived from the prevention of the methane release coupled with its radiation-trapping properties.

This section examines the potential for renewable electricity technologies to reduce U.S. carbon emissions. The contributions of renewables in various end-use sectors, such as transportation, are discussed in other chapters in this report.

Renewables are in the midst of a major, long-term transition, from being "advanced technologies" with only a peripheral market role to becoming mainstream "technologies of choice" in the energy marketplace early in the next century. One clear marker of this transition is the changing cost of electricity from renewable power technologies. Figure 7.10 displays these costs for the period from 1980 to 2005, based on both historical data and recent projections (Office of Utility Technologies, 1997).

Figure 7.10 Historical and Projected Costs of Electricity from Four Renewable Power Technologies



The pace and timing of this transition is difficult to project, however, because it is strongly dependent on such variables as the progress made through research and development, the evolution of energy economy policies, and the magnitude and impact of consumer interest in "green" energy. For example, under the $50/MtC cost-of-carbon scenario assumed in this study, the adoption of wind power in the United States is likely to increase rapidly on an economic basis. In addition, increasing attention is being focused on consumer interest in green energy. As the electric utility sector moves toward competitive markets, consumers probably will have the option of purchasing power that is environmentally cleaner.

The rate of change will impact the role of renewables in 2010 at least as much as the specific energy contribution of renewables in that year. Therefore, this section discusses the trends as well as the predicted contributions of renewables to the energy supply and to carbon emission reductions in 2010.

A thorough analysis of the role of renewables in 2010, which captures the complexity of their transition, has not been conducted as a part of this study. Instead, this section presents analyses of a few renewable technologies whose role is likely to be quite significant by 2010, and includes a general discussion of the other renewable technologies. A more thorough analysis of the relationship between renewables and reductions in carbon emissions over a longer time frame is the subject of a future study.

Thus, this section discusses the role of renewables in two time frames: (1) developments and contributions by 2010, and (2) the long-term outlook.

7.3.1 Renewable Electricity in 2010

As stated earlier, renewable electric technologies will make important contributions to carbon emission reductions in 2010 in the context of a policy that imposes a $50/tonne cost on carbon emissions. Estimates of those contributions are presented here. While the scope of this study did not include a thorough and systematic analysis of this issue, the estimates given are based on a number of directly relevant studies. These include, in particular, carefully developed performance and cost projections for renewable electric technologies (Office of Utility Technologies, 1997) and projections of future market penetrations of these technologies (Office of Energy Efficiency and Renewable Energy, 1997).

The potential of biomass cofiring was assessed because that technology provides an opportunity for reasonably straightforward displacement of a significant amount of coal. This assessment, which draws upon another recent analysis, is presented first.

An analysis of the impact of a $50/tonne cost of carbon on wind power was also conducted, and those results are discussed second. Wind was selected because cost projections for wind power indicate that this technology will be competitive with other electricity generation sources according to the electricity costs modeled in the HE/LC scenario of this study. In addition, wind power is already successfully penetrating electricity markets in the United States and abroad.

This analysis is followed by estimates of carbon emission reductions that would be likely to result from hydropower upgrades and landfill gas capture and use. These estimates are derived from DOE and EPA studies relevant to market projections for those two technologies, respectively (Rinehart et al., 1997; EPA, 1993).

Finally, other key renewable power technologies are discussed briefly. We present estimates of the likely contribution of these technologies in 2010, developed through comparisons and extrapolations from earlier projections (Office of Energy Efficiency and Renewable Energy, 1997).

7.3.1.1 Cofiring Coal with Biomass

Cofiring biomass with coal has the technical and economic potential to replace at least 8 GW of the nation's coal-based generating capacity by 2010, and as much as 26 GW by 2020. Though the current substitution rate is negligible, a rapid expansion is possible with the use of wood residues (urban wood, pallets, and secondary manufacturing products) and dedicated feedstock supply systems (DFSS) such as willow, poplar, and switchgrass.

The current coal-fired power-generating system represents a direct opportunity for carbon mitigation by substituting biomass-based renewable carbon for fossil carbon. Extensive demonstrations and trials have shown that biomass can replace up to about 15% of the total energy input with little more than burner and feed-intake system modifications to existing stations (CONEG, 1996). Since large-scale power boilers in today's 310-GW-capacity fleet range from 100 MW to 1.3 GW, the biomass potential in a single boiler ranges from 15-150 MW.

Preparation of biomass to an appropriate size of less than one-quarter inch, with a moisture content of less than 25%, can be achieved using existing commercial technologies. "Tuning" the combustion output of the boilers causes little loss in total efficiency, implying that the biomass-to-electricity combustion efficiency is close to the 33-37% range of an unmodified coal plant, an efficiency that stand-alone biomass generating capacity has yet to demonstrate.

Economics

The cost of implementing biomass cofiring varies from site to site. It is influenced by the space available for yarding and storing the biomass, the installation of size-reduction and drying facilities, and the nature of the boiler burner modifications required. The cost is expected to be in the range of \$100-\$700/kW of biomass capacity. Early trials indicate that a median value of about \$180/kW is likely. A 100-MW coal plant with 10% biomass substitution would then require an investment of \$1.8 million. There is an O&M cost increase of \$70,000/year over coal, as a result of the need for an additional yard worker to handle the biomass. Assuming a GENCO recovers its investment cost in three years, the annual fuel offset then has to be \$670,000 to cover capital recovery (\$1.8 million) and increased O&M costs (\$210,000 for three years). If the average price of coal is about \$1.40/MBtu (million Btu), the annual fuel cost of coal is \$1.081 million (10 MW of biomass capacity at 85% capacity factor and 32.9% thermal efficiency, 10,337 Btu/kWh). The allowable cost of biomass then is \$411,000, or about \$9/tonne. Above this cost, the biomass would have to be subsidized to encourage a GENCO to use biomass cofiring.

Fuel Costs

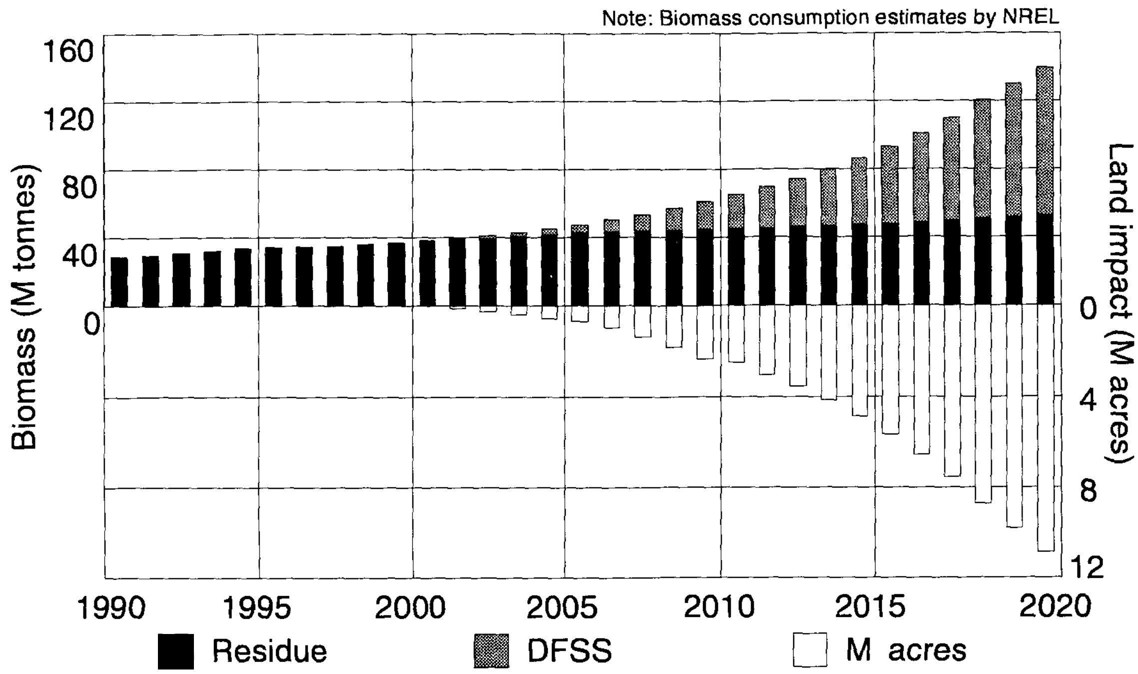
Near-term potential biomass feedstocks are those residues available within a radius of about 50 miles around a plant. Data from existing biomass power plants in the Northeast and California indicate that there are extensive sources of biomass residues available for about \$0.50/MBtu (less than \$9/tonne). Transportation costs limit the range over which such biomass feedstocks can be acquired and, in the long term, there are likely to be dedicated feedstock systems much closer to the power plants. By definition, residues (e.g., urban wood residues, rights-of-way clearance, construction and demolition wood, pallets, and sawdust shavings from secondary wood processing) are finite and will respond to the prices offered for them.

Dedicated feedstocks would not be bound by this constraint. However, such feedstocks are much more expensive than residues. With current technology the price is about \$2/MBtu, although the current development goal is in the range of \$1-\$1.50/MBtu. It is assumed that an estimated 10.4 million acres will be needed to reach a nominal production of 86 Mt by 2020. Because DFSS is in an early stage of development, the model assumes that the initial planting will yield only about 6 tonnes/acre by 2002 (today's state-of-the-art), and that by 2010 the yield will be closer to 8 tonnes/acre. Today's costs are high; \$45/tonne is feasible, but a combination of learning-curve improvements and economies of scale should bring the cost down to about \$32/tonne by 2010. The competing coal price is assumed to be \$1.40/MBtu (\$1.33/GJ) throughout.

Biomass Substitution Potential

The cofiring estimates in this section were derived from a 30 GW scenario for all biomass technologies, developed by NREL for the current Biomass Power Program Strategic Plan. This scenario is for a mix of steam, cofiring, and integrated gasification/combined cycle (IGCC) biomass generation. However, the resource plan that was developed, which included residues and DFSS, is independent of the end use and involves the development of 11-12 million acres of land for DFSS by 2020, or just under 3 million acres by 2010. The resource development shown in Figure 7.11 is used as the basis for this carbon assessment. This indicates that DFSS would come on rapidly after the year 2001 and assumes that residues would be capable of only a small increase in quantity, since much is already being utilized. The average cost of residues is expected to increase gradually, while the cost of DFSS crops is expected to demonstrate a strong learning curve and large economies of scale.

Figure 7.11 30 GW Strategic Plan Scenario



Timing

While a coal-fired station could be modified for cofiring in less than one year (including environmental permitting), a biomass resource assessment, contractual arrangements, and logistics for biomass residues could take the better part of 18 months, based on actual project experience. Although the availability of residues is assumed to be significant and would ultimately supply about 50 Mt, price and availability are likely to be variable. The price will no doubt increase with the level of demand; therefore, the biomass feedstock supply is expected to be a blend of DFSS and residues.

The DFSS component is predicated on making a start on land accumulation (whether purchases, leases, or cooperatives), with land preparation and planting in 1999. A significant effort will be required to initiate development of the 11-12 million acres proposed for 2020; today, discussions are about DFSS demonstrations at the 1000-acre level. Adequate clonal material and management systems for planting, tending, and harvesting will also need to be developed. The crops of choice in much of the Northeast and Southeast are probably woody species, which would require extensive nursery activity to put the needed clonal material in place for planting out. With willow, the first harvest cycle would be four years after planting and a rotation of three years thereafter. For poplar, the cycle is likely to be in the range of six to eight years.

Environmental Issues

Because biomass generally contains significantly less sulfur than coal, cofiring with biomass could reduce SOx emissions. Early results suggest that there is also a NOx reduction potential using woody biomass. However, most coal-fired power stations have efficient precipitators and some have sulfur-capture technologies, so the net environmental effect of 10% biomass substitution (on an energy basis) appears to be negligible. The solid wastes (ash) would be little changed in either composition or mass (most biomass has considerably less ash than coal). But some stations sell fly ash to Portland cement manufacturers, so there may be a need to negotiate the acceptance of mixed biomass and coal ash in such applications with respect to ASTM standards.

The DFSS environmental impact is dependent on the choice of lands for plantations. Replacing annual cropland with perennial DFSS appears to result in a net environmental gain. Results for pasture land are probably negligible and replacement of forest may result in some increased impacts.

The use of residue has the potential to offset landfilling as well as potential methane emissions from landfilling clean biomass materials. Experiences in California indicate that the issue will be one of rationalizing the cost distribution between the waste generator, the hauling contractor, and the generating station receiving the residue rather than it going to a landfill. If such negotiations were successful, and the generating station could guarantee reception of the residues at all times (many urban wood residue generators do not have storage facilities), both residue costs and their availability could improve significantly.

Impact on Carbon Emissions

Given the technical and economic potential described above, it is probably reasonable to assume additional biomass-cofired capacity of 8-12 GW by 2010, which should reduce carbon emissions by 16-24 MtC.

7.3.1.2 Wind Power

The development of wind power systems has progressed quite rapidly since 1980. There are approximately 1800 MW of wind capacity operating in the United States today, and another 4300 MW of capacity overseas (Figure 7.12). This capacity growth is almost certain to continue because of continuing decreases in the cost of wind-generated electricity as well as growing interest in emission-free power derived from local, renewable resources. Figure 7.13 shows the projected cost of wind-generated electricity for wind farms located in Class 4 and Class 6 resource sites (as presented in DOE's 1997 Technology Characterizations). Class 4 sites have average wind speeds of 5.6-6.0 m/s, Class 6 sites have average wind speeds of 6.4-7.0 m/s, both measured at a height of 10 meters. Figure 7.13 also displays the median, 10th percentile, and 90th percentile of electricity generation prices in 2010 based on the HE/LC case described in Chapter 6. As these projections indicate, wind power prices are projected to drop below the median 2010 price for that scenario before 2005. Thus, strictly on a price-of-energy basis, in this scenario wind power will be able to compete favorably with other power sources for several years prior to 2010.

In addition to the price of energy, a number of other factors will affect the extent to which wind power systems will be adopted between now and 2010. These include, for example, the overall market for new power systems, the price penalty that wind power will encounter for providing intermittent power, and the price advantages that wind power will realize because it is a "green" power source and because it is not subject to the risk of future fuel price increases. Because the level of influence of each of these factors has not been analyzed, it is difficult to project their combined impact.

Figure 7.12 Domestic and International Wind Power Capacity, Grid-Connected

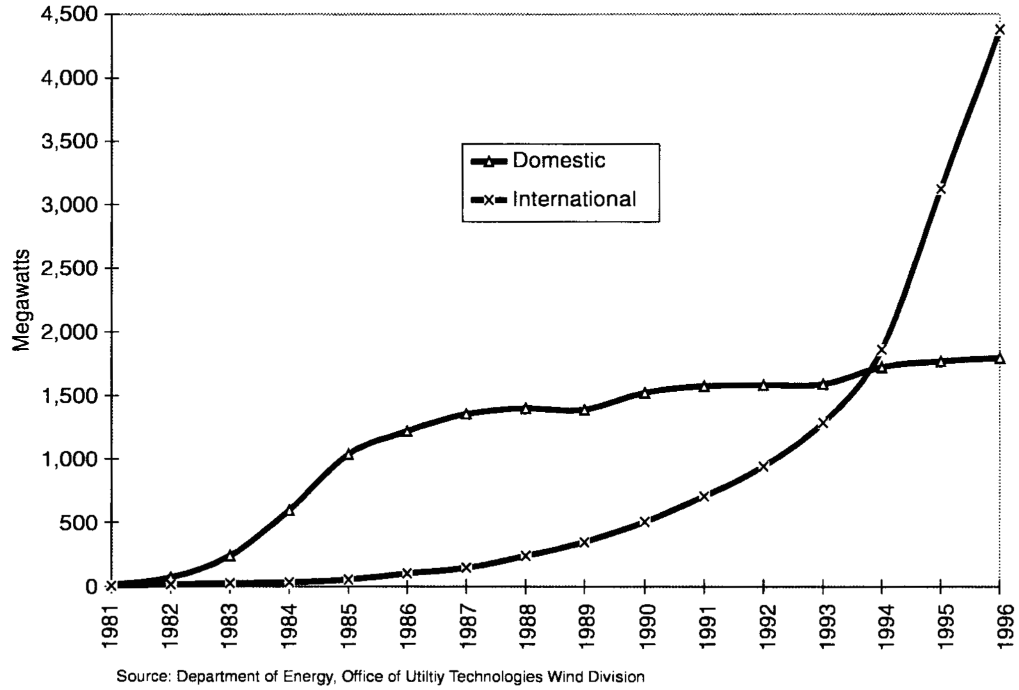
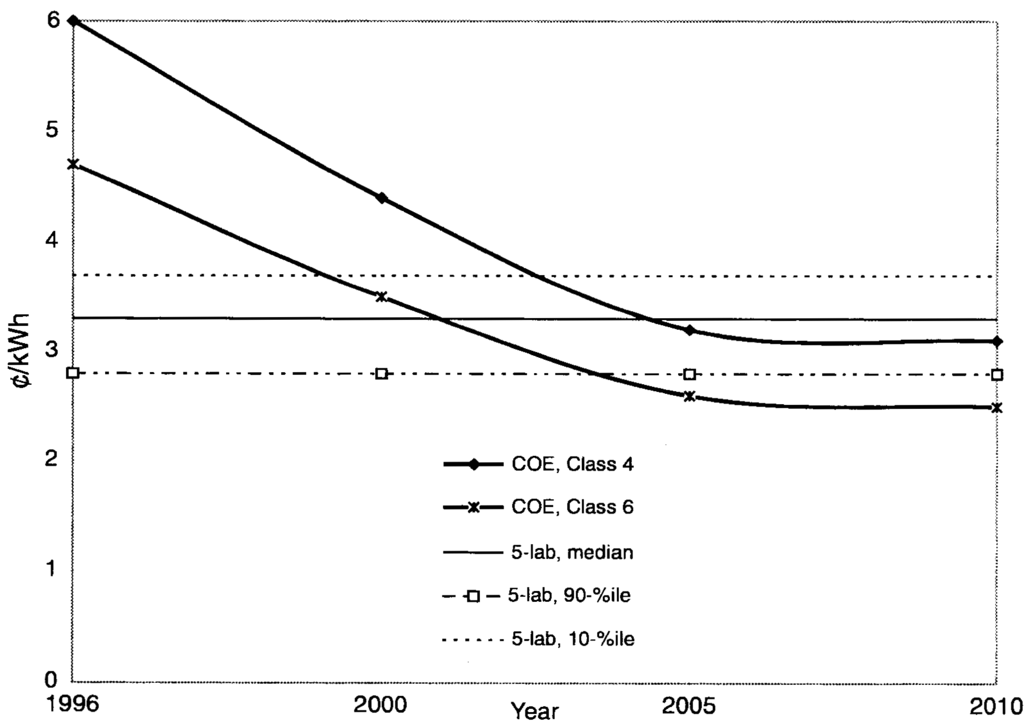


Figure 7.13 Projections of Wind Power Costs



In the AEO97 reference case forecast, EIA projects electricity generation to increase by about 800 TWh by 2010, from 3083 TWh in 1995 to 3874 TWh in 2010 (EIA, 1996). In this context, EIA projects a total of only 3800 MW of wind generating capacity. The Quality Metrics analysis by the Office of Energy Efficiency and Renewable Energy (EERE) of the impacts of its R&D program estimates that additional installed wind power generating capacity will reach 8 GW and contribute approximately 29 TWh to the electricity market by 2010 if wind program goals are met. This will result in a carbon emission reduction of 6 MtC. Neither of these projections, however, assumes a major new market policy to promote wind power.

In the HE/LC case of this study, electricity generation will increase by significantly less than in the business-as-usual case. Thus, the HE/LC scenario presents a much smaller target market for new power-generation sources. However, under the transition of the utility sector to a competitive market, it is very likely that newer technologies with lower generating costs will displace some existing generation capacity with higher generating costs. Moreover, in the HE/LC scenario, generation costs are projected to be more than 25% higher than in the base case. Thus, as illustrated in Figure 7.13, wind power generation costs will be highly competitive in this marketplace, so displacement of higher-cost existing generation by wind is likely. In an attempt to model the penetration of wind under these conditions, the ORCED model was run using the wind technology characteristics developed by the Office of Utility Technologies (Office of Utility Technologies, 1997). As might be expected, the results indicated that the level of wind penetration in this case is quite sensitive to the actual input parameters. According to the model, for example, using the cost and performance characteristics projected by DOE for the year 2005 could lead to the adoption of as much as 50,000 MW of wind power by 2010. Using 160 kg/MWh, the average carbon intensity of the generation displaced (see Chapter 6), this would result in a carbon emission reduction of 28 MtC. Because the ORCED model indicated that this new wind capacity would displace coal-fired generation, a higher conversion ratio (275 kg/MMh) is used to estimate carbon emission reductions, resulting in an estimated reduction of 48 MtC.

This level of penetration would require wind-turbine manufacturing capacity to expand at a rate of approximately 25% per year. As Figure 7.12 indicates, this level of wind capacity expansion has been reached in the past. Europe's experience with wind power also indicates that this technology can expand quite rapidly. It is possible for the manufacturing industry to respond quickly to market demands, since most of the components of wind systems (generators and gearboxes) are readily available, and not specific to wind technology. In 1991, the European Wind Energy Association set a goal of 4 GW of wind by 2000. This goal has been realized already in 1997, and the new targets are 8 GW by 2000 and 40 GW by 2010. Given that Europe is a much more land-constrained continent with generally lower wind resources than the United States, this comparison suggests that 50 GW of wind power capacity can be realized in the United States by 2010 in the context of a strong policy environment.

The HE/LC context of this analysis assumes a policy environment that acknowledges the need to address global warming. In such an environment, renewable energy, including wind power, will be able to demand somewhat higher prices because of consumers' preferences for green power. The value of that premium is not yet known.

It is well-documented that wind resources in the United States are quite extensive. For example, an assessment of wind resources and access to transmission indicates that more than 115 GW of Class 5 and Class 6 sites are within 5 miles of existing lines, and more than 1,000 GW Class 4 sites are within that same range (Parsons et al., 1995). This assessment excludes sites that are not suitable for wind farm development, such as cities and wilderness areas. Thus, 50 GW could probably be developed primarily in Class 5 and Class 6 areas, which means that they will operate with relatively high capacity factors and low costs of energy. (The Draft Technology Characterizations indicate that capacity factors will be 45% in Class 6 regions and 35% in Class 4 regions by 2005.)

This analysis does not take into account the fact that wind-generated electricity will probably face at least a partial price discounting because wind power is not fully predictable. At this time, the level of this discounting is simply not known. To date, with low levels of penetration into grid-connected generation, intermittency has not been an issue. There are some indications that the range of electricity prices in a competitive market will be fairly narrow. For example, prices for electricity transactions on the Continental Power Exchange during peak hours generally vary only by about 2 cents/kWh (Continental Power Exchange, 1997). This implies that price variations between different generation sources cannot vary by more than that, and it is likely that the difference will be much smaller under full competition.

In summary, analyses indicate that total wind power capacity in 2010 could range from as low as 5 GW, based on a simple extrapolation of today's energy economy, to as high as 50 GW in an environment that includes competitive pricing and policies emphasizing control of carbon emissions. Given these results, it is probably reasonable to estimate that additional wind capacity will be 8-23 GW in 2010. This translates into electricity contributions of 28-81 TWh, resulting in reductions of carbon emissions of 6-20 MtC relative to the BAU forecast for 2010.

7.3.1.3 Increasing Generation and Capacity at Existing Hydropower Plants

Hydroelectric power currently supplies about 10% (78 GW) of the nation's electricity and constitutes 84% of the nation's generation from renewables (EIA, 1996). Hydroelectric power plants produce no greenhouse gas emissions during operation (DOE, 1994). In the 1940s, 40% of the country's electricity came from hydropower plants (Williams and Bateman, 1995). The adverse environmental affects of some hydropower projects are now relatively well known (e.g., Mattice, 1991), but significant progress is also being made in mitigating these problems (Sale et al., 1991).

Hydroelectric power uses the energy of falling water to generate electricity. Hydroelectric generation technologies for utility-scale applications are generally considered to be mature, with turbine efficiencies typically in the 75%-85% range (OTA, 1995). There are three types of hydropower facility:

1. Most hydropower plants use dams to raise the water level, which increases the water's potential energy, and allows for regulation of the water availability. Conventional hydropower (with reservoir storage) can provide baseload, intermediate, or peaking power, depending on the availability of water and project design (OTA, 1995).

2. Run-of-river systems do not use large dams or storage reservoirs. Instead, smaller diversion structures are used to channel some of the water through a canal or penstock to a powerhouse, after which the water is returned to the river. Run-of-river systems avoid some of the costs and environmental impacts associated with large hydro facilities.

3. Pumped storage projects use off-peak electricity (usually from a baseload power plant) to pump water to an upper reservoir; this water is later released to flow through a generator during periods of peak demand. Such plants are net consumers of energy. Although pumped storage is not a renewable energy technology, it can result in a net reduction in greenhouse gas emissions when the fuel providing electricity for pumping has a lower carbon content than the fuel being displaced by the pumped storage generation (DOE, 1994).

The main challenge for hydropower in recent years has been the growing concern over its local environmental impact. By damming rivers to create storage reservoirs, hydro facilities can have an adverse effect on terrestrial and aquatic ecosystems. Wildlife habitats can become inundated. Fish migration routes can be cut off, and fish can die in the generating turbines or because the downstream water quality and habitat are changed. Plants that grow along the riverbanks can be disrupted by changes in the natural water level, both above and below the dam, and large or rapid variations in the amount of water being discharged can disrupt aquatic habitats and accelerate erosion downstream.

Regulatory measures — such as the licensing of non-federal hydropower projects and the Endangered Species Act — are reducing the environmental impact of hydropower projects, but they are also reducing total electricity production from this energy source. Between 1995 and 2010, 19 GW of hydropower at non-federal projects will be subject to relicensing. Recent trends indicate that relicensing results in an average 8% loss in generation due to the imposition of new environmental constraints on operation.

Under the HE/LC scenario, and assuming a sustained regulatory reinvention effort between now and the year 2010, incentives could be in place to increase hydroelectric power generation in either of two ways. Neither of these opportunities involves the construction of hydropower plants at new sites. However, both will require continued R&D to improve the design of turbine systems and to minimize adverse environmental effects:

- Increasing generation at existing hydropower plants. This option consists of modernizing and upgrading existing turbines and generators to increase their efficiency and/or electrical output. With enabling incentives, upgrading hydropower plants can result in energy production gains of 5%-10%. Hydropower upgrades would also have significant environmental benefits, because new generating technologies offer improved fish passage, better water quality, and new opportunities for improving downstream aquatic habitats.

- Adding generating capacity at existing dams. A recent resource assessment identified 20 GW of undeveloped hydropower capacity at existing dams (Rinehart et al., 1997). About 36,000 GWh of new hydropower generation could be added by developing these sites between 1995 and 2010 (Office of Conservation and Renewable Energy, 1990).

Further expansion of hydropower capacity is possible, but unlikely until after 2010. The national hydropower resource assessment (Rinehart et al., 1997) has identified an additional 11 GW of environmentally acceptable hydropower at undeveloped sites (those requiring the construction of new dams or diversions). These resources may eventually be developed, given more advantageous economics, regulatory reinvention, and/or technology improvements. Further development of efficient low-head generating technologies would encourage deployment at the many low-head sites that are currently unsuitable for hydropower additions.

Considering only the near-term options, and the fact that there may be some loss of hydropower capacity due to relicensing issues and environmental mitigation regulations, net capacity additions by 2010 could be 10-16 GW, reducing emissions by 3-5 MtC. Additional carbon savings can be achieved after 2010 with continuing advancements in generating technologies and environmental mitigation techniques.

7.3.1.4 Landfill Gas

When food scraps and other organic wastes in landfills decompose, they produce methane. Methane is a potent greenhouse gas that is also the main ingredient of natural gas. According to the Intergovernmental Panel on Climate Change, each kilogram of methane is about 21 times more effective at trapping radiation in the atmosphere than a kilogram of carbon dioxide. Landfills are the largest source of anthropogenic methane emissions in the United States; they are responsible for almost 40% of these emissions each year (EPA, 1997).

New EPA regulations require operators to seal larger, closed landfills with a special cap, collect the gas, and burn it to prevent atmospheric releases of methane. But wells sunk into landfills can capture the gas before it escapes the surface. It can then be used for a variety of applications, including generating electricity.

Today, about 165 landfills recover and utilize methane as a fuel. Various estimates (Governmental Advisory Associates, 1994; EPA, 1997) indicate that between 300 and 750 of the country's 3500 landfills could economically recover methane using currently available technologies. The development of more efficient, less expensive technologies for gas recovery, clean-up, and utilization could accelerate the adoption of landfill gas-to-energy systems. For example, highly efficient, experimental fuel cells have operated on landfill gas processed using new clean-up technology.

By 2010, 0.2-0.5 quads of energy per year could be recovered from the methane in landfills and converted to electricity. Taking into account the difference in the radiative effects of methane and CO_2, this represents the equivalent of 25-53 MtC in reduced emissions (DOE, 1994).

7.3.1.5 Other Renewable Power Technologies

This section examines three more renewable electric technologies: photovoltaics (PV), geothermal power, and solar thermal power. Figure 7.10 illustrates that the costs for these three technologies have also decreased sharply over the past 15 years. It is very likely that this trend will continue. While none of these technologies are expected to contribute as much electricity as biomass cofiring or wind power by 2010, their role in 2010 electricity markets may be significant and growing.

Photovoltaics

Photovoltaics (PV) uses solar cells to generate electricity from sunlight without any emissions or moving parts. This technology has made substantial progress since its first successful application in space. While PV power costs are still significantly higher than the costs of other renewable technologies, sales of PV power systems have been growing steadily, probably because of the many unique advantages of PV. These include modularity (applications can range from solar calculators to power stations), widespread applicability (since adequate solar resources are widely available), and ease of integration into the built environment (through incorporation into building facades, roofing materials, highway sound barriers, parking-lot structures, etc.). The most important application of PV today is in stand-alone systems that provide power to remote water pumps or off-grid residences, for example. Because approximately two billion people live in villages without grid electricity, remote power represents a very large and important market for PV in developing countries.

For grid-connected applications, one of the most promising trends in the past few years is "building-integrated" PV. Numerous buildings have been constructed — primarily in Europe, Japan, and the United States — that incorporate PV panels in windows, awnings, or roofing materials. Thus, the PV panels serve a dual function, which effectively lowers the cost of their role as power generators. In these applications, the PV power directly displaces grid electricity at the end point of the delivery system, where it has the greatest value. Another advantage of PV is that its peak power output generally coincides with peak electricity demand, which further enhances its market value.

Worldwide sales of PV power systems have grown to nearly 100 MW per year, up from 10 MW in 1982, an average annual growth rate of about 20%. This rate of growth is likely to increase as a result of numerous programs promoting PV for village power in developing countries as well as programs promoting greater use of PV in several developed nations. One example is the U.S. Million Solar Roofs program, announced by President Clinton at the United Nations on June 26, 1997. Others include Japan's Sunshine Project, Germany's subsidy of up to 70% of PV system costs, and Switzerland's PV Schools Program.

EIA estimates that total installed PV capacity in the United States will be only 0-2 GW in 2010 (EIA, 1996). However, an independent assessment of the impact of DOE's R&D programs indicates that, by 2010, installed U.S. PV capacity will be approximately 1.3 GW under a BAU scenario (Office of Energy Efficiency and Renewable Energy, 1997). Using this as a starting point, and considering the many advantages of PV, an estimate of installed capacity of 4-7 GW in 2010 is probably reasonable for the HE/LC scenario. This would provide 6-13 TWh of electricity and reduce carbon emissions by 1-2 MtC. One important addition to PV capacity will come from the recently announced Million Roofs Initiative, which will result in 1-2 GW of new capacity.

The market trends for PV in 2010 are probably more significant than its energy and carbon contributions. By 2010, PV energy prices will be substantially lower than they are today, and we will have had considerably more experience with the development and use of building-integrated PV products. In this context, the United States will be moving into a situation in which a significant and increasing fraction of construction includes PV generation capabilities.

Geothermal Electricity

Geothermal power technologies use the thermal energy from underground reservoirs of hot water or steam to produce electricity. With higher temperature resources, the steam is used to drive a turbine directly; with lower temperature resources, a binary technology is used in which the hot water vaporizes another working fluid, which then drives a turbine. These geothermal power-generation technologies are considered fairly mature. The major challenge lies in locating and characterizing the size and longevity of specific geothermal reservoirs.

Approximately 3 GW of geothermal capacity is installed in the United States today. While EIA estimates that geothermal capacity will increase by only 0.2 GW by 2010 (EIA, 1996), DOE's recent Quality Metrics Study indicates that geothermal power capacity will increase by 5.8 GW, and electricity production will increase about 45 TWh, in a BAU scenario (Office of Energy Efficiency and Renewable Energy, 1997). While a \$50/tonne cost of carbon would improve the economics for geothermal, it is not expected to provide as much of a boost as it does for wind or biomass. It is probably reasonable to use the DOE estimate as the lower boundary, and project that total installed geothermal power capacity in 2010 under the HE/LC case will be 8-16 GW. The 6-14 GW increase in geothermal capacity over today's level would reduce carbon emissions by 6-16 MtC.

Solar Thermal Electric Technology

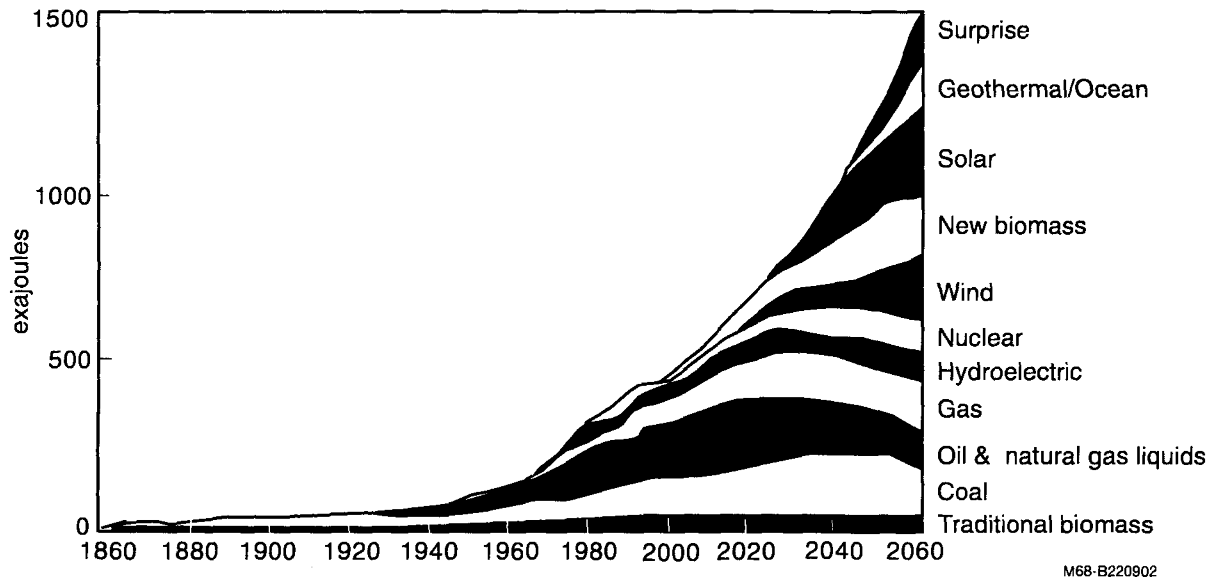
Solar thermal power technologies use mirrors to concentrate direct sunlight onto a thermal receiver, thus creating a high-temperature energy source that can be used with a heat engine to generate electricity. There are three types of solar thermal power systems: parabolic troughs, power towers, and dish/engine systems. Parabolic trough systems use large fields of linear parabolic reflectors, each of which heats a fluid flowing through a receiver pipe located along the focal line of the reflector. About 350 MW of these systems are operating in California. A 10-MW demonstration of a solar thermal power-tower system, which uses large mirrors to direct solar rays to a thermal receiver atop a tower, is also operating in California. The third technology uses individual parabolic dish reflectors to provide thermal energy to a Stirling engine mounted at the focal point of the dish. A few individual prototype units, which have power outputs of about 10-25 kW each, are being tested in the United States.

While EIA projects negligible gains for solar thermal generating capacity by 2010 (EIA. 1996), DOE's recent Quality Metrics Study suggests that solar thermal systems will provide approximately 2 TWh of electricity in 2010 in a BAU scenario (Office of Energy Efficiency and Renewable Energy, 1997). Under the HE/LC scenario of this study, an estimate of 0-2 GW capacity and 0-6 TWh electricity generation in 2010 is probably reasonable. This would reduce carbon emissions about 0-1 MtC.

7.3.2 The Long-Term Role of Renewables

As indicated at the beginning of this section, it is quite likely that renewable energy technologies will play a crucial role in limiting carbon emissions and global warming in the long term. Continued domestic and international economic development that does not foster further global warming will require greater energy consumption coupled with lower carbon emissions. The only options are thus low-carbon energy supplies, such as nuclear power or renewables, or the sequestration of carbon emissions from the use of fossil fuels. With the continuing technological development and cost reductions of renewables, renewables may become preferred energy resources some time within the next one to three decades. Moreover, they will probably expand to become the world's primary energy resource in the latter half of the next century. In fact, just such a transition was suggested recently by Shell International (Figure 7.14) (Royal Dutch/Shell Group of Companies, 1996).

Figure 7.14 Sustained Growth Scenario from Shell International (Reproduced courtesy of Shell International Petroleum Company)



This subsection describes the future direction and likely accomplishments of continuing R&D in renewables. This discussion should lend credence to the prediction that non-hydro renewables will make the transition from a minor to a major contributor to the world's electricity supplies.

Biomass Power

The most important R&D areas for biomass power are in gasification/conversion systems and in feedstock production. Gasification involves converting the solid biomass feedstock material to a gas that is cleaned and then burned in a combustion turbine or used in a combined-cycle plant. This technology is currently in the initial demonstration stage of development.

The importance of this technology is that it can take advantage of advanced turbine designs and heat-recovery steam generators to achieve almost twice the efficiency of currently installed biomass technologies (NREL estimates, 1997). High-pressure gasification technologies yield the highest efficiencies, but they also require the development of efficient, cost-effective methods for cleaning the hot gases before they enter the turbine.

On the biomass production side, genetic research is likely to produce energy crop species that provide consistently higher biomass yields on an energy-content basis, thus providing a proportional reduction in biomass feedstock costs. Related research into new species designed for better fuel production also looks promising in terms of significantly decreasing biofuels costs over time. Research into advanced agricultural methods will also lower feedstock production costs over time. Finally, the development of simpler feedstock handling and processing methods will also lead to lower costs. Whole-tree processing methods, for example, which avoid the cost of chipping the wood before processing or use, could reduce the cost of harvesting and delivering the biomass to the power plant by about one-third (OTA, 1995).

Taken together, improvements in biomass power conversion as well as feedstock production and processing could reduce the cost of electricity from biomass to about 3-4 cents/kWh. This would make biomass power very economical in comparison to other mainstream electricity sources. As biomass power expands, most of it will employ dedicated feedstocks. In this context, biomass use will entail low net carbon emissions. These net emissions primarily result from the combustion of fossil fuels in production and delivery, because the carbon emitted during conversion will be reabsorbed as new feedstock grows. Thus, biomass power can become a major contributor to reducing overall carbon emissions from electricity generation in the coming decades.

Wind Power

The technological and economic feasibility of wind power — both in the United States and abroad — has already been well established, as the wind generation capacity curves in Figure 7.12 indicate. Nonetheless, major advances for wind power technology in both the short-term and long-term are likely. These are predicted for the short-term by DOE's cost and performance projections (Office of Utility Technologies, 1997), as illustrated in Figure 7.13.

Wind turbine design is the most critical R&D area. In general terms, the research goals are to produce turbine designs that have half of the material content of today's turbines, at perhaps three-quarters of the material cost (to account for more expensive materials), but with higher efficiencies and longer lifetimes. Such design improvements will not only lower the cost of wind-generated electricity, they will also make it economically practical to utilize the widespread, somewhat lower quality wind resources found in Class 4 wind regimes. Some of the critical research needed to achieve these goals includes continued empirical research into the air-turbine blade interface, computational fluid dynamics modeling of that interaction, and fatigue testing and structural modeling coupled with materials research. This is all aimed at producing more efficient turbine blades that minimize material utilization while extending blade operating lifetimes.

Another important area of R&D concerns the development of direct-drive generators and improved power electronics. This will yield higher conversion efficiencies and more durable power-conversion components, eliminating the need for a gearbox in the drive train. A major challenge will be the integration of advanced components and controls into large-scale, utility-class hardware.

There is also considerable room for improvement in turbine manufacturing processes through process development and automation, since today's turbine blades are still largely built by hand.

A fourth critical research area is that of wind prospecting and prediction. Wind regimes are extremely site-specific, so even though wind resources have been broadly categorized for the nation and the world as a whole, the siting of individual wind farms requires detailed information in order to select the best site. Wind speeds can vary dramatically over the course of seconds (due to turbulence), hours (diurnal variations), days (weather fronts), and months (seasonal variations). The best locations are those with strong, sustained winds having little turbulence. Finding such locations requires extensive prospecting and monitoring (OTA, 1995). The development of better tools for resource characterization and prediction will both improve the economics of wind power and enhance its value by enabling utilities to more reliably predict the power output from specific wind power plants.

Another important thrust for research is to address siting issues. For example, the tops of ridges are often good wind sites, but such a visible location for a wind farm can be a cause for concern when the site is either close to a population center or in an area of particularly great scenic value. To date, there have been virtually no studies to understand the local values associated with the visual impact of wind systems relative to other energy technologies in the United States. Yet such analysis could play a key role in decisions about the adoption of wind power in specific regions. Another environmental consideration affecting site selection is the potential risk to birds, particularly raptors, which sometimes fly into the rapidly turning rotor blades. This, too, seems like an issue that may well be resolved through research to understand the scope of the problem relative to other threats to bird species as well as the development of ways to keep birds a safe distance from moving turbine blades.

In summary, the research front for wind power technology is very broad. Achievements are likely to lead to widespread adoption and application of this electric power technology throughout the world, wherever resources are adequate, over the next few decades.

Geothermal Electricity

Both current geothermal power systems and advanced geothermal power technology concepts will benefit from continuing R&D.

Today's geothermal power plants use the thermal energy from hot water and steam in hydrothermal reservoirs to generate electricity. While the power conversion and drilling technologies related to these power plants are considered relatively mature, they will also benefit from R&D in heat exchangers, hot fluid management systems, and new thermal conversion cycles. These activities alone could result in energy cost reductions of at least 20% in the next few years (NREL estimates, 1997).

The most important R&D area for conventional geothermal technology is resource exploration and characterization. The cost of geothermal electricity is highly dependent on resource characteristics such as temperature, depth, sustainable extraction rate, fluid chemistry, and ease of drilling. By 2020, improvements in drilling technology, advanced seismic data gathering, and better computer modeling and interpretation of the data could lower the average cost of locating and assessing geothermal resources by 50% (NREL estimates, 1997).

In the long term, geothermal power plants could make use of hot dry rock resources — areas of exceptionally hot rock (above 150°C) that have little or no water in them. Energy can be extracted from these zones by injecting water from the surface underground, where it is heated. Although the engineering feasibility of extracting energy from hot dry rock has already been demonstrated (Secretary of Energy Advisory Board, 1995), further R&D is necessary to make the technology commercially viable. With success in that endeavor, the potential for geothermal power would be vastly expanded because hot dry rock resources are widely available.

Photovoltaic Power Systems

Although PV power technology has already experienced major gains in both performance and economics as a result of R&D conducted over the past 30-40 years, there is still considerable potential for further improvements. This is true for essentially all aspects of PV power systems, including research on basic photovoltaic materials, development of high-efficiency PV cells and modules, development of better PV power products, lower cost manufacturing processes, and improvements in the various components of PV systems.

A good example of the potential of PV R&D is found by comparing the module efficiencies of current commercial PV modules with the efficiencies of individual solar cells. For crystalline silicon PV technology, the technology representing about 90% of current sales, commercial module efficiencies are generally between 10% and 15%, while the best laboratory cell efficiencies are well above 20%. For thin-film PV technology, which includes amorphous silicon, copper indium diselenide, and cadmium telluride modules, current module efficiencies are generally well under 10%, but cell efficiencies are above 15%. Thus, in all cases, progress in commercial products would be virtually assured through the replication of established laboratory results. There is also clearly the potential for greater increases in cell efficiencies over today's laboratory results. Some of the research tools that are being applied include computer modeling of various semiconductor materials and atomic-level engineering of new devices to better understand their photovoltaic and electronic properties.

Looking ahead, we find that significantly greater efficiencies are possible. For example, multi-junction cells have been tested with efficiencies above 30%. At this time, these are small, laboratory-scale devices whose initial application is expected to be with concentrators, in which the cost of the cell is significantly offset by the increased solar energy captured by the optical concentrator. However, in a decade or two, it is certainly conceivable that low-cost processes for making similar high-efficiency multi-junction devices will have been developed, which will make it possible to use them in conventional, flat-plate PV modules.

In the area of manufacturing processes, considerable effort is being made to perfect processes that provide uniform, high-quality materials for the thin-film technologies. The fruits of these efforts are likely to be realized in the next few years as a number of firms construct fairly large (5-20 MW per year) manufacturing plants based on the results of process research and development.

There is still considerable progress to be made in the development of PV power products. For example, many PV power systems today are still being individually designed for specific applications. Off-the-shelf PV power systems and consumer products (such as PV walk-lights, lanterns, and battery chargers) are becoming more available, but the commercial PV industry is still a long way from making it as easy to purchase a residential PV system as it is to buy a refrigerator. The development of products that are readily applied to such individual needs will have an important effect on PV electricity costs because it will increase the volume of sales. A particularly important set of PV products is likely to be PV components for building shells. These include windows, wall materials, awnings, and roofing materials that incorporate PV and are as readily installed as the components they replace in today's building industry. A reasonable long-term target is to have a large fraction of new construction incorporate such building-integrated PV products.

Finally, we will continue to see improvements in the balance-of-system components of PV systems. Examples include power conditioners and controllers, which serve as the electrical operating and interface system for integrating PV power modules with the load and/or the power grid. These components will continue to improve as well as benefit from developments in power electronics. Greater system integration is also likely, simplifying overall system design. A good example is the development of PV modules that incorporate dc-to-ac inverters, an activity that is currently under way.

In summary, PV technology will benefit from major R&D advances for many years to come, and these advances will significantly improve the economics of PV power. Among the implications of these advances, it is likely that PV power systems will reach prices of $3000/kW by 2010, which is less than half the current average price. Further price reductions will no doubt occur beyond that.

Solar Thermal Electricity

Solar thermal technologies will benefit from R&D in a broad range of areas. For example, successful development of durable silver/polymer reflectors will reduce reflector costs by 25% to 50% for all three technologies, reducing system costs by 10% to 20%. Improved reflectors and receivers will also allow higher operating temperatures and thus higher solar-to-electric conversion efficiencies. Technology advances for Stirling engines will directly benefit dish/engine systems; one of the most important areas is the extension of operating lifetimes between overhauls. The development and application of hybrid solar/natural gas systems will be particularly important for power tower and parabolic trough technologies. These will make it possible to provide dispatchable power and to use combined-cycle technology, as well as smaller solar fields without being penalized by smaller steam turbines, which tend to be less efficient.

By 2020, we are likely to see power-tower conversion efficiencies around 30%, compared with about 15% today, and dish/engine conversion efficiencies of about 35%, up from about 25% in current prototypes. At the same time, these technologies will cost less and be more durable. At this stage, they are likely to be fully competitive with other mainstream power technologies in areas with good solar resources throughout the United States and the rest of the world.

7.4 EFFICIENCY IMPROVEMENTS IN GENERATION AND TRANSMISSION & DISTRIBUTION

Lowering the heat rates of fossil-fueled generation results in greater efficiency (i.e., less fuel burned per electricity generated) and lower carbon emissions. OTA (1991, p. 320), for instance, suggests that improved maintenance could reduce heat rates by 5%, resulting in a reduction of 22 million tonnes of carbon emissions by the year 2000. OTA includes this measure in their "moderate" scenario, viewing it as either a low-cost or a no-cost measure. The rate of improvement assumed by OTA is consistent with a power plant performance monitoring and improvement project conducted by the Electric Power Research Institute (1986; 1989). Hirst and Baxter (1997) also note the value of cutting heat rates for fossil-fuel power plants, as a carbon reduction option. No efficiency improvements to existing fossil plants are assumed in the 1997 *Annual Energy Outlook's* reference case (Schouberlein, 1997).

The Southern Company has had extensive experience with improving the efficiency of their electric utility system. Over a thirteen-year period, the Southern Company was able to reduce its heat rate by 5.8%, lowering it from approximately 10,300 Btu/kWh (in 1982) to less than 9,700 Btu/kWh (in 1994) (Southern Company, 1993; Siegel, 1997). This represents an improvement in fossil system efficiency from approximately 33.2% (in 1982) to 34.8% (in 1994). The current level of efficiency in U.S. fossil-fired power plants is approximately 33%. In addition to improving the company's system-wide heat rate, the Southern Company was able to increase its reliability from 88% (in 1982) to 96% (in 1994) (Southern Electric International, 1996), and was able to increase its availability to approximately 86%. The current availability of U.S. fossil-fired power plants is approximately 81%.

These heat rate and availability improvements to the Southern Company's electric system have provided benefits valued at $1.1 billion/year. One of the largest benefits to the Southern Company has been from the deferral of 6,000 MW of new capacity. The cost of these heat rate and reliability improvements to the Southern Company is estimated at approximately $325 million/year. The operation and maintenance activities that comprise these costs include: establishing a heat rate improvement training program, creation of a plant heat rate review board and a system heat rate technical network, assignment of an efficiency engineer at each plant, instituting a program of heat rate monitoring, and investing in design upgrades (Siegel, 1997).

The Southern Company's experience is consistent with the OTA and EPRI estimate that a 5% heat rate improvement is technically feasible at a low cost or at no cost. Such an improvement would result in a concomitant reduction of 5% in the carbon emissions of the utility sector. Based on Chapter 6's HE/LC case (Table 6.4), the electricity sector's carbon emissions in 2010 would be 492 MtC. Although coal generation accounts for only 46.2% of the electricity generation forecasted for 2010, coal plants account for 81% (or 400 MtC) of the carbon produced by the electricity sector. A 5% reduction would represent 20 Mt of carbon emissions. Assuming that 35-65% of this total is feasible, a realistic estimate of the potential reduction is 7-13 MtC.

Improving the efficiency of transmission and distribution (T&D) systems is another supply-side option available to utilities. As with generation, T&D improvements can include both capital investments (for example, new transformers and conductors) and improved operations. Because T&D losses account for only about 7% of total generation, the opportunities to reduce CO_2 emissions through such mechanisms are limited. However, they could nonetheless be cost-effective. Improving T&D efficiency by 10% would cut emissions by almost 1% (Hirst and Baxter, 1997).

7.5 NUCLEAR PLANT LIFE EXTENSION

In both the AEO97 reference case and the restructured case described in Chapter 6, nuclear plants are projected to lose market share in the national mix of electricity generation. Similar trends are forecast worldwide, with the forecasted decline in nuclear power in Europe being particularly large (South, et al., 1997).

In the U.S., the nuclear power capacity of 99.2 gigawatts that existed in 1995 is projected to drop to 88.9 gigawatts in both the AEO97 reference case and the restructured case in 2010. This drop is primarily the result of the retirement of 17 plants whose licenses expire between 1999 and 2010. The combined capacity of these 17 plants is 11.5 gigawatts. The average capacity factor of the remaining plants ranges from 76-79% throughout the forecast, deviating little from the current capacity factor of 77%.

No additional nuclear units are actively under construction in the U.S. Therefore, no new planned units are assumed to come into service during the 2010 forecast. One nuclear unit, Watts Bar 1 owned by the Tennessee Valley Authority, received its license in 1996, but a few plants have also recently closed.

Nuclear power is a carbon-free source of electricity. Retaining as much as possible of its current power generation would therefore be an important carbon mitigation strategy in an economy where carbon emissions bear a charge of $50 per tonne, as in the HE/LC scenario.

AEO97 defines a "high nuclear case" which assumes that every nuclear plant operating in 1996 has an additional 10 years of operation, as long as their operating costs do not exceed 4 cents/kWh. This 2010 forecast results in the closure of only three nuclear plants (totaling 1.3 gigawatts of capacity) due to license expirations and the addition of 10.2 gigawatts of new capacity from 14 plant lifetime extensions (EIA, 1996; Nuclear Regulatory Commission, 1996). Thus, nuclear capacity in EIA's forecast for 2010 grows from 88.9 gigawatts (in the reference case) to 99.1 gigawatts (in the "high nuclear case"). Based on a capacity factor of 77%, this 10.2 gigawatts of capacity expansion from nuclear plant life extensions results in 69,000 GWh of additional nuclear energy in 2010, compared to the reference case.

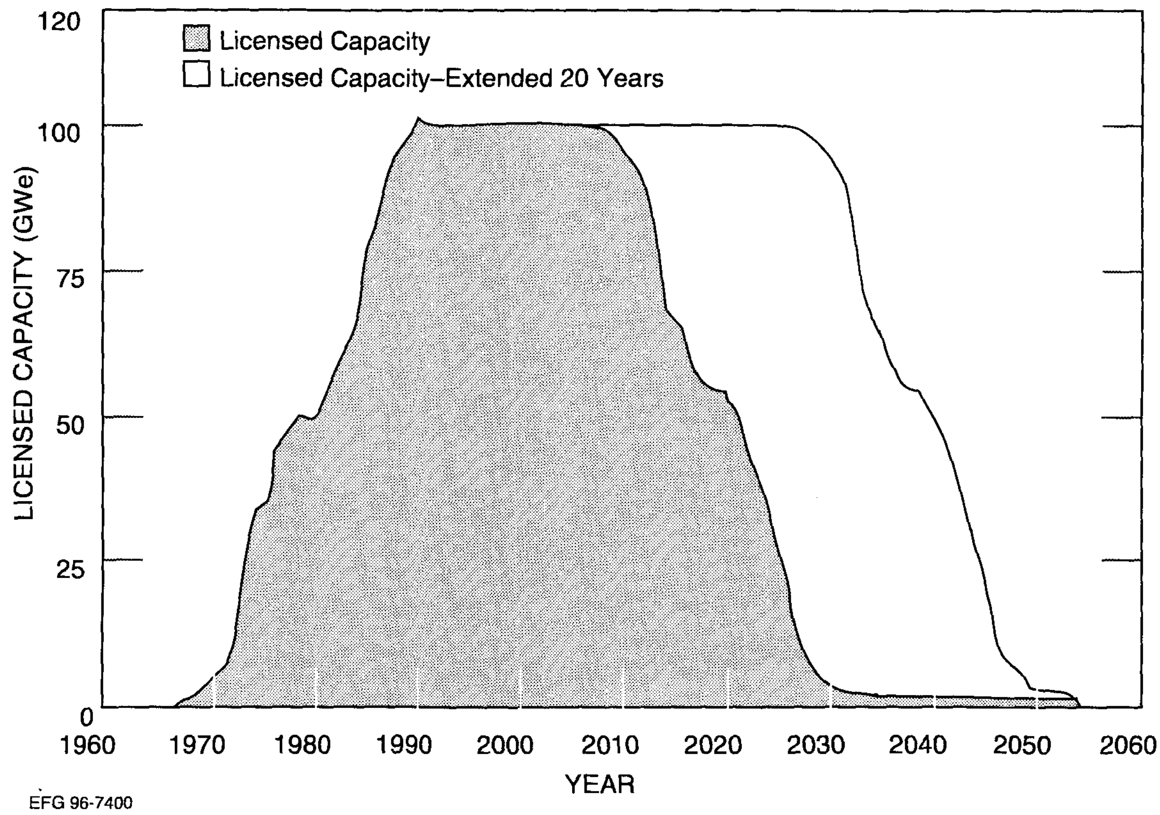
According to EIA's "high nuclear case," 12 Mt of carbon would be offset by this additional carbon-free source of electricity. Using the capacity on the margin in the HE/LC case (with carbon emissions averaging 160 tonnes/GWh), we estimate that the carbon reductions from this additional nuclear resource drop to 11 MtC. A range of 4-7 MtC (from 35-65% of this potential) would appear to be a more realistic forecast for the HE/LC scenario. This range recognizes that it will not be economical or politically feasible to extend the operation of nuclear power plants with licenses that expire by the year 2010.

The AEO97 reference case forecasts that nuclear capacity in the U.S. will decline at an increasing pace after 2010, decreasing from 88.9 gigawatts in 2010 to 62.7 gigawatts in 2015. Thus, with the demand for energy continuing to grow, the impact of nuclear power as a carbon offset declines precipitously over this slightly longer planning horizon. Under the "high nuclear case," the assumed 10-year nuclear plant licensing extensions (subject to the 4 cents/kWh maximum cost) increases nuclear capacity in 2015 from 62.7 gigawatts (in the reference case) to 94.7 gigawatts (in the "high nuclear case"), Thus, the magnitude of carbon offsets offered by this strategy becomes quite significant after 2010.

Figure 7.15 illustrates the accelerated role that nuclear power life extension could have in offsetting carbon emissions after 2010. Only 45 of the nation's 105 nuclear plants have licenses that extend beyond 2020 (Nuclear Regulatory Commission, 1996). An effort to maintain the viability of this capacity could result in a very large contribution to carbon reductions over the next quarter century.

AEO97 does not estimate the cost of its "high nuclear case," although it acknowledges that the physical degradation of some units would have to be reversed. OTA (1991) also notes the potential carbon savings of extending the useful life of all nuclear plants to 45 years, but assumes that this option involves either low costs or saves money. Understanding the effects of aging in order to better manage the aging nuclear infrastructure is an important R&D topic. Pressure vessel embrittlement and the degradation of cables, pumps, and valves can be better managed by advances in materials science and by developing and implementing advanced monitoring technologies. Such technologies are the result of R&D and help maintain the current licensing basis of the nation's nuclear power plants, thereby enabling their operation to extend beyond the initial 40-year licensing period.

Figure 7.15 U.S. Commercial Nuclear Power Reactor Generating Capacity



7.6 ADVANCED COAL TECHNOLOGIES

To test the possible effects on carbon emissions of other advanced fossil-fired electricity generation technologies, we replaced the advanced technologies used by EIA with estimates from DOE's Office of Fossil Energy (see Table 7.6). These estimates changed the construction costs and heat rates for advanced combustion turbines, combined-cycle units, and coal units. ORCED did not select the advanced coal unit with either the EIA or the Fossil Energy estimates of this unit's costs and operating characteristics; in both cases, its initial cost was too high to warrant inclusion in the generation mix. The only significant change to occur was the replacement of the most advanced combustion turbine as specified by EIA with an older combined cycle unit. The net effect of this change on carbon emissions was negligible.

This limited analysis suggests that between now and the year 2010, highly efficient (i.e., a heat rate of about 7000 Btu/kWh) but expensive (i.e., a cost of over $1000/kW) advanced coal units cannot compete economically with either the generation mix that remains from the 1990s or with gas-fired combined-cycle units.

Table 7.6 Base Case Technologies Compared to Advanced Technologies (costs in 1995$)

	Original	Alternative	Original	Alternative
Advanced Gas Combined Cycle				
Year of construction	2005	2005	2009	2010
Capital Cost, $/kW	410	525	410	500
Heat Rate	6284	5688	5817	5538
Fixed O&M, $/kW-yr	27	16	27	16
Variable O&M, ¢/kWh	0.05	0.015	0.05	0.015
Advanced Gas Combustion Turbine				
Year of construction	2002	2005	2008	2010
Capital Cost, $/kW	339	400	374	364
Heat Rate	10873	8699	7793	8533
Fixed O&M, $/kW-yr	11.9	17.6	16.9	17.6
Variable O&M, ¢/kWh	0.010	0.012	0.05	0.012
Advanced Coal				
Year of construction	2006	2005		
Capital Cost, $/kW	1340	1050		
Heat Rate	9600	7064		
Fixed O&M, $/kW-yr	34	26		
Variable O&M, ¢/kWh	0.25	0.2		

7.7 SUMMARY

Table 7.7 summarizes the potential reductions in carbon emissions that could occur as the result of the technology options discussed in this chapter. Each option is intended to reflect roughly the amount that could be achieved under aggressive policies combined with a carbon incentive of approximately $50/tonne. The total carbon reductions from the options shown in Table 7.7 range from 80 to 117 MtC by the year 2010. Additional carbon reductions may result from landfill gas recovery, photovoltaics, geothermal, and solar thermal resources.

The analysis of renewable energy potential over the next quarter century indicates that with a vigorous and sustained program of research, development, and deployment, renewable energy technologies could be providing a greater and rapidly growing contribution to electricity generation by the year 2020. The potential contributions of carbon sequestration, advanced coal technology, and nuclear power were not explored in this report.

Table 7.7 Carbon Reduction Potential of Selected Electricity Supply Technology Options in the HE/LC Scenario with Carbon Permit Price of $50/tonne

	High-Efficiency/Low-Carbon Case (MtC)
Converting coal-based power plants to natural gas	44
Cofiring coal with biomass	16-24
Wind	6-20
Hydropower	3-9
Efficiency Improvements	7-13
Extending the life of existing nuclear plants	4-7
Total	80-117

7.8 REFERENCES

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ENDNOTES

[1] Other approaches include (1) repowering with an advanced coal technology (integrated coal gasification combined cycle (IGCC), or pressurized fluidized bed combustion (PFBC)) or (2) plant performance (efficiency) improvements through various management and technical adjustments. With both of these "other" repowering options, the carbon emissions reduction potential is not as great as with NGCC due to (1) the magnitude of efficiency improvement and (2) the carbon (together with sulfur and nitrogen) content of coal versus natural gas.

[2] All coal-fired power plants greater than 50 MW, and projected to remain in operation, were considered for NGCC repowering: 22.5 gigawatts (GW) of capacity identified by EIA in AEO97 to be uneconomic were deleted, as were 47.5 GW determined to be unneeded due to end-use energy efficiency improvements (see Section 6). Appendix G-2 discusses the deletion of this capacity from the coal/gas repowering analysis.

[3] One million Btu (MBtu) is the equivalent of one thousand cubic feet (MCF) of natural gas. One trillion cubic feet of natural gas is abbreviated as TCF.

[4] This estimate of gas transmission cost may be high, since it may overestimate the amount of interstate and intrastate pipeline that is needed to serve the repowered capacity. Alternatively, since the costs are averaged over all candidate plants based on gas volume delivered to the repowered site, it may approximate the diseconomies of scale that might arise in expanding compression or building new pipeline to serve only a limited amount of repowered capacity.

[5] A constant 1995 gas/coal price differential assumes that (1) end-use energy efficiency has an offsetting effect on increased utility gas consumption and/or (2) extraction/production costs for natural gas decline at the same rate as the increase in demand.

[6] The gas/coal price differential of $0.72/MBtu represents the 1995 value as reported by EIA in its Annual Energy Outlook (AEO97). It represents a lower bound value, since the differential remains constant over time (and demand), reflecting no price response by the natural gas industry with increasing utility fuel demand. The $1.18/MBtu reflects the 2010 gas/coal price differential within AEO97. This differential reflects a real natural gas price increase of $0.40/MBtu ($2.04/MBtu in 1995 to $2.44/MBtu in 2010) and a 1.9 TCF increase in utility gas demand.

[7] "Partial Repowering" is equivalent to the "no additional transmission cost" case.