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**5 Labs Study:
Scenarios of U.S. Carbon Reductions**

**Department of Energy
June 10, 1997 Draft**

**Joe Aldy
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DRAFT

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U. S. CARBON REDUCTIONS BY 2010 AND BEYOND

The Potential Impact of Energy-Efficient and Low-Carbon Technologies

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

June 11, 1997

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AUTHORSHIP

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Other sections of this chapter are summaries of published materials.

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DRAFT
EXECUTIVE SUMMARY
June 9, 1997

This report presents the results of a multi-laboratory study aimed at quantifying the potential for energy-efficient and low-carbon technologies to reduce carbon emissions in the United States. The stimulus for this study derives from a growing recognition of the link between energy efficiency R&D and the nation's ability to respond to international calls to reduce the growth of greenhouse gas emissions. We describe the reductions in carbon emissions that can be attained through increased penetration by 2010 of energy-efficient technologies, many of which resulted from past R&D activities. We also provide a view of the potential for future research to lead to further carbon reductions. As such, this report underscores the value of energy efficiency technology research, development and diffusion as a public response to global warming.

OBJECTIVES OF THE REPORT

The purposes of this study are fourfold:

- (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 technologies;
- (2) to document the costs and performance of the energy-efficient technologies that underpin a year 2010 scenario in which energy savings and carbon emissions reductions are achieved;
- (3) to also assess the carbon reduction potential by 2010 of selected low-carbon technologies for end users and for the electricity supply sector, and
- (4) 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.

METHODOLOGY

To achieve these objectives, we started with the *Annual Energy Outlook 1997* (AEO '97) 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 either to accept them as is (which was the option chosen for buildings and industry), or to modify some of the assumptions and data and produce a new "business-as-usual" (BAU) scenario (which was the option chosen for 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 is 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.



We then estimated 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 two cases other than the "business as usual" case. We have termed the first the "efficiency" case. It assumes that the Nation increases its emphasis on energy efficiency through enhanced public- and private-sector efforts. This case was designed to be achievable without major changes in our way of doing business in energy. The general philosophy of the "efficiency" case is that it reduces, but does not eliminate, various market barriers and lags to the adaptation of cost-effective energy efficiency technology.

The other case, dubbed the "high efficiency/low carbon" case, assumes a greater commitment to reducing carbon emissions through federal policies and programs, strengthened state programs, and very active private sector involvement. This includes a focused national R&D effort to develop and transform markets for low-carbon energy options (e.g., biofuels for automobiles). This case describes 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. Our analysis describes one such result of a national endeavor that strives to reduce carbon at the lowest incremental cost. In this case, we assume a domestic trading scheme for carbon emissions, with a domestic permit price of \$50/tonne carbon.

For one fuel – electricity – we examine the impact of the efficiency scenarios on prices. The same detailed assessment of the electricity supply system was conducted to estimate the carbon emissions that would be displaced under the efficiency scenarios.

In addition to the work focusing on 2010, we peered beyond. Here our methodology is to focus on new technologies, materials, processes, manufacturing methods, and other R&D advances that promise to offer significant energy benefits by the year 2020, but where specific levels of market penetration, energy savings, and carbon reductions are difficult to forecast. Thus, instead of building scenarios we describe the technological innovations that could, if appropriate investments in R&D are made, form a basis for significant changes in the way we use energy.

BACKGROUND

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. Between 1973 and 1986, the nation's consumption of primary energy froze at about 74 quads – while the GNP grew by 35 percent. 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 carbon emissions have been increasing at a similar pace.

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

Nevertheless, many cost-effective energy-efficient technologies remain underutilized. A host of market barriers account for these lost opportunities. And declining energy R&D expenditures are causing further technology opportunities 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. Second, 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.

① sketchy
② is light

The benefits to past public investments in energy efficiency R&D have been well documented. Between 1975 and 1995, DOE spent approximately \$8 billion on energy-efficiency R&D. Five of the technologies that were developed or demonstrated with a fraction of this DOE support have saved consumers an estimated \$28 billion in energy bills. DOE's portfolio of energy efficiency R&D has also led to significant environmental, health, and economic competitiveness benefits, as well.

RESULTS

Prospects for Improved Efficiencies by the Year 2010

Table A.1 and Figure A.1 compare the nation's primary energy use in quads for the years 1990 and 1997 with the results of the three scenarios for 2010.

Table A.1 Primary Energy Use in Quads: 1990-2010

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

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

11.6% ↓ from BAU

6.6% ↓ from BAU

The major observations from these 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) followed by industry (4.8 quads) and then buildings (2.3 quads) in the BAU case. 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 forecast by the BAU case. Relative to the BAU case, the efficiency scenario for transportation delivers slightly more energy savings (3.1 quads) than do efficiency scenarios for the industrial (2.0) or buildings (1.9) sectors. Compared with 1997 levels, the smallest increase in energy growth for the efficiency case is in buildings (0.4 quads), followed by industry (2.8 quads), and transportation (3.7 quads).
- The "high efficiency/low carbon" scenario 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. Compared with 1997 levels, buildings is down about 2 quads and industry and transportation are up 1 and 2 quads respectively.

Figure A.1 Primary Energy Use in Quads: 1990-2010

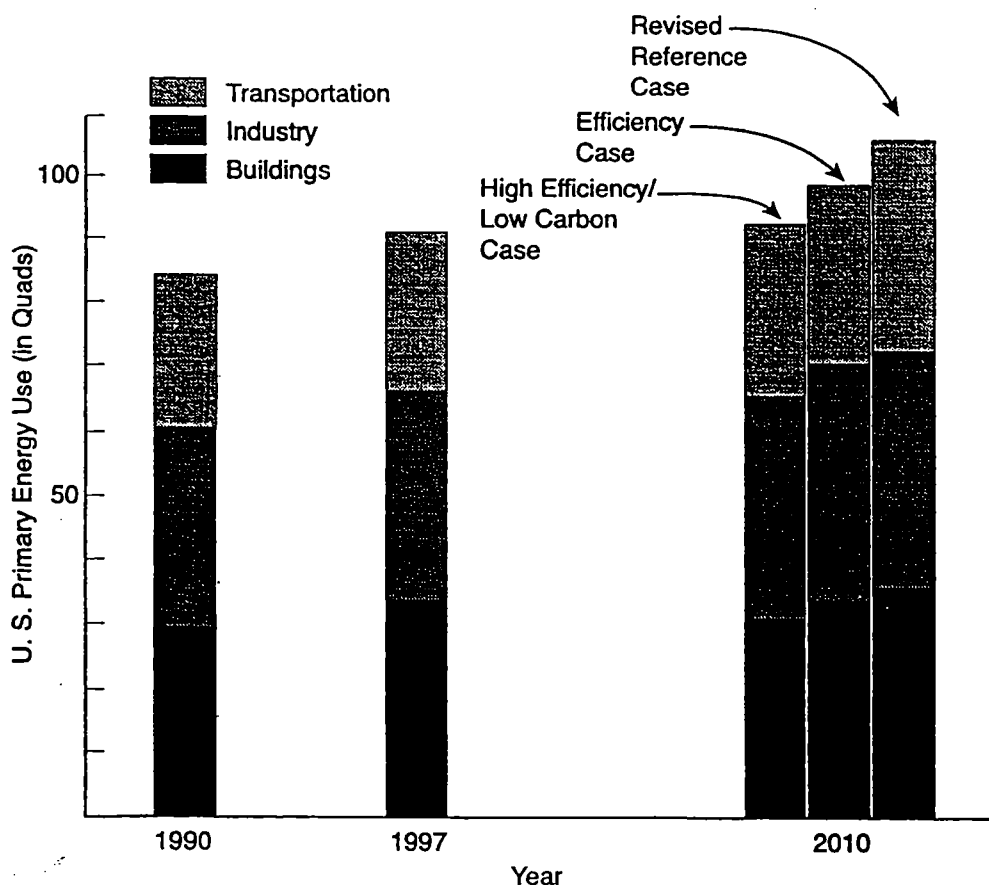


Table A.2 documents the impact of these projected energy savings in 2010 on carbon emissions in that same year. It also presents the results of a more complete "high efficiency/low carbon" scenario, which characterizes the impacts of including the high level of efficiency improvements along with two additional types of low-carbon technologies.

- It includes end-use carbon reductions that do not result entirely from reduced energy consumption, but rather result from either fuel switching or by displacing carbon from industrial processes. Specifically, the buildings sector includes stationary fuel cells for cogeneration, and the industrial sector includes advanced turbine systems, biomass gasification, inert anodes and wettable cathodes in the aluminum industry, and slag cement. These carbon reductions were not included in the "high efficiency/low carbon" models for buildings and industry; rather, they are based on additional case studies.
- It also includes a number of electricity supply technologies that could reduce carbon emissions in the year 2010 under the conditions characterized by the "high efficiency/low carbon" scenario..

Table A.2 Carbon Emissions (in million metric tons): 1990-2010

	2010 ^a					
	1990	1997	Business-as-Usual Case	Efficiency Case	High Efficiency Case (w/o Low-Carbon Technologies)	High Efficiency/Low Carbon Case ^b
Buildings	460	511	571	546	532	525 to 530
Industry	452	482	534	512	494	461 to 483
Transportation	432	486	616	543	513	513
Utilities ^c	-	-	-	-	-	-157 to -138
Total (rounded)	1340	1480	1720	1600	1540	1340 to 1390

^aThese carbon forecasts for 2010 represent our best "point estimates." The precision of these estimates is unknown, since none of the forecasts used in this report are based on parameters with known probability distributions.

^bThis scenario includes the carbon emission reductions resulting from a carbon permit price of \$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 sector.

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

The major observations from the above table are:

- In the BAU case, carbon emissions are forecast to increase by approximately 380 million metric tons (MtC) (from 1340 to 1720, or 28%) between 1990 and 2010.
- The energy efficiency gains incorporated in the "efficiency" case cut overall growth between 1990 and 2010 by one third (from 380 to 260 million metric tons). This represents carbon increases of 19% above the emissions in 1990.

\$50/ton
C permits

- The energy efficiency improvements spurred by the "high efficiency" case reduce overall growth between 1990 and 2010 by an additional 60 MtC (decreasing the increase from 380 to 200 million metric tons or 15% above the emissions in 1990).
- The conversion of electrical generation from coal to natural gas and the preferential dispatch, combined with the use of added low carbon technologies, primarily in the industrial sector, reduce carbon emissions by an additional 150 to 200 MtC. In this case, which we estimate to cost less than \$50/tonne of carbon (for the additional 150 to 200 MtC), results in approximate carbon stabilization in 2010 at the 1990 level (0 to 30 MtC increase).
- Approximately 140 MtC of the increase in carbon emissions between 1990 and 2010 will have occurred by the end of 1997; thus, it is useful to look at the 13-year forecast starting with 1997. The carbon reductions incorporated in the efficiency case cut the overall growth in carbon emissions between 1997 and 2010 from 240 million tons (as forecast in the BAU case) to 120. The "high efficiency/low carbon" scenario reduces carbon emissions in 2010 to about 115 MtC (90 to 140 MtC) below the 1997 level.

Table A.3 provides a comparison of the growth rate in energy and in carbon emissions for the three cases, from 1990 to 2010. In general, the growth in carbon emissions tracks the increase in energy demand, with carbon growing slightly more rapidly than energy in the efficiency case. This is because the efficiency scenario reduces the need for constructing new low-carbon (combustion turbine and natural gas combined cycle) power plants and therefore results in a generation mix that has a higher percentage of coal-based electricity than would be true with the "business-as-usual" case. In all three scenarios, carbon emissions increase more slowly than the GDP, indicating a net "decarbonization" of the U.S. economy.

Table A.3 Average Annual Energy and Carbon Growth Rates, 1990 to 2010, for Three Cases

	Revised AEO Reference Case	Efficiency Case	High Efficiency/ Low Carbon Case
Energy Demand	1.14%	0.80%	0.52%
Carbon Emissions	1.24%	0.88%	0 to 0.2%
Energy Consumption Per GDP (E/GDP)	-0.74%	-1.08%	-1.35%
Carbon Emissions Per GDP (C/GDP)	-0.64%	-1.00%	-1.7 to -1.9%%

*Note that these changes in carbon emissions are for the entire period, including the seven years that have already occurred. The carbon decrease per unit GDP growth for 1997 to 2010 is 0.7, 1.25, and 2.3 to 2.5 percent per year for the reference, efficiency, and high efficiency cases, respectively.

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

a 20% to 35% emissions reduction relative to 1987 levels, or emissions levels of 0.85 to 1.0 MtC/year of carbon in 2015. Our "efficiency" and "high efficiency/low carbon" cases of 1.3 to 1.6 billion metric tons of carbon emissions in 2010 is comparable to OTA's "moderate" case and shows considerably higher emissions than OTA's "tough" case.

Another benchmark is provided by the 1992 National Academy of Sciences (NAS) report on *Policy Implications of Greenhouse Warming* (National Academy of Sciences, 1992). This study identified a set of energy conservation technologies that had either a positive economic return or that had a cost of less than \$2.50 per tonne of carbon. Altogether, NAS concluded that these technologies offer the potential to reduce carbon emissions by 463 million tons, with more than half of these reductions arising from cost-effective investments in building energy efficiency. Our "efficiency" and "high efficiency/low carbon" cases suggest the potential for reducing carbon emissions by between 120 and 380 million metric tons by the year 2010. This is about one-fourth to one-third of the potential estimated by the NAS. One of the reasons for this difference is that the NAS study did not deal with a particular planning horizon. 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 technologies.

R&D's Potential for Further Benefits by 2020

If carbon reductions in 2010 and beyond are to be sustained, aggressive R&D efforts are needed to produce a pipeline of next-generation energy technologies. It is difficult to estimate the energy and carbon savings that will accrue from these technologies; however, an effort to characterize their features suggests that an aggressive pace of energy and carbon savings over the next quarter century can be sustained.

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 integrated into smaller packages that cost less, can withstand harsh environments, and are able to characterize and optimize currently impenetrable systems without disturbance. 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 by the year 2020. Examples of specific technology opportunities are described in this report, by sector.

Six R&D areas are forecast to offer great promise to reduce significantly the energy requirements of our Nation's buildings in 2020: construction methods, adaptive building envelopes, multi-functional equipment and advanced appliances, advanced lighting systems, controls and communications, and self-powered buildings.

Improvements in energy efficiency and carbon reductions in industry beyond 2010 require further R&D to spawn new and improved technologies. In addition to the broad application of better process modeling, sensors, and controls mentioned above, many process/industry-specific opportunities for efficiency gains exist. These are described for each of DOE's targeted industries of the future: pulp and paper, chemicals, petroleum refining, glass, aluminum, iron and steel, and metal casting.

Many of the advanced technologies that have the potential to significantly improve the energy efficiency of transportation after 2010 need considerable R&D investment before they can

become commercially available in the year 2020. For example, to achieve fuel economies in the 60-80 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 to improve the energy efficiency of other transportation modes are described.

With a vigorous and sustained program of research, development and deployment, renewable energy technologies could provide a greater and rapidly growing contribution to electricity generation by the year 2020. In combination, hydroelectric, wind, biomass, photovoltaic, geothermal, and solar thermal power options could deliver significant quantities of electricity in 2020 as a means of reducing carbon emissions.

The technology opportunities envisioned for the year 2020 will not materialize without strong public-private partnerships to support the array of R&D and market transformation activities needed to ensure that cost-effective products and practices are available and deployed.

ASSESSMENT OF COSTS AND SOURCES OF CARBON REDUCTIONS

The "business-as-usual" scenario projects an increase of 380 million tonnes/year of carbon between 1990 and 2010. In our efficiency case, 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. A very strongly accelerated drive to promote energy efficiency could lead to reductions of 180 MtC/year (high efficiency case). Under a carbon cap and trading system, in which permits for carbon sell for \$50/tonne C, very substantial carbon reductions appear possible. Results for these three cases, showing the sources of the carbon reductions, are contained in Table A.4. The indicate that, for the high efficiency/low carbon case, there is a potential to roughly return to 1990 levels of carbon emissions in 2010 at a cost of less than \$50/tonne carbon.

It is important to recognize that there are significant uncertainties in the analysis and many factors that will determine the degree to which and the costs of achieving the carbon reductions shown in Table A.4. We present below a summary of the expected technology costs in 2010, as well as the cost of implementing a carbon permit system. While these costs are necessarily uncertain, they are our best estimates and, in our view, as likely to be high as to be low. We note, however, that we have confined our analysis to technology costs, and have not assessed policies or programs to achieve market acceptance.

Emissions reductions of 120 to 180 of the 380 MtC needed to achieve stabilization in 2010 result from energy efficiency measures which, based on the data presented in the report, are on balance cost-effective. Ignoring the implementation costs, this means that the cost of reducing carbon emissions are negative overall. Unless there are serious difficulties in implementing the measures, the costs of 120 MtC/year will be close to zero. The next 60 MtC/year - which includes substantially increased implementation of energy efficiency measures for buildings (from 35% of potential cost-effective measures to 65%), increases in ethanol as automotive fuel and the use of more advanced (and costly) energy efficiency technologies for transportation, and both reductions in hurdle rates as well as market lags for industry - will have a very low cost. As indicated in the individual sector discussions, the technology for the high efficiency case is for the most part likely to be cost-effective or near cost-effective in 2010 but there is somewhat more uncertainty about the ability to achieve market acceptance.

**Table A.4 Potential Reductions in Carbon Emissions to Achieve 1990 Levels in 2010,
in Million Metric Tons of Carbon
(Reductions are from Business of Usual Case)**

	Efficiency Case	High Efficiency Case (w/o Low Carbon Technology)	High Efficiency/Low Carbon Case: High
Buildings			
Energy Efficiency	25	39	39
Fuel Cells	0		2 - 7
Industry			
Energy Efficiency	22	40	40
Advanced Turbine Systems	0		5 - 17
Aluminum Technologies	0		2 - 4
Biomass Gasification	0		2 - 10
Cement	0		2
Transportation			
Energy Efficiency & Ethanol	73	103	103
Utility Supply Options			
Carbon-Ordered Dispatching	0		77
Converting coal-based power plants to natural gas	0		50*
Cofiring coal with biomass	0		5 - 20
Extending the life of existing nuclear plants	0		2 - 5
Hydropower expansions	0		4 - 5
Total (rounded)	120	180	330 - 380

*The potential for converting coal-based power plants to natural gas is much greater than 50 MtC/year, as described in chapter 7. However, the cost-effectiveness of the conversion is highly sensitive to the magnitude of the coal permit charge, the externality value of NO_x, and, and the relative price of natural gas and coal. If natural gas prices are, for example, \$10/tonne C higher (lower) than anticipated in the report, then a \$60 (\$40)/tonne C permit price would be needed to achieve 50MtC/year reductions. Because the cost curve of carbon from this source is relatively flat, it may be possible to significant increase the carbon reductions subject to availability of natural gas.

Note: the results in this table are undergoing review at this time. As a result, there may be some changes in numbers. We do not, however, anticipate major changes.

The utility sector provides a substantial part of the next increment of carbon reductions: 125 MtC/year are achieved through increased costs associated with the dispatch of higher-cost electricity (using natural gas power plants in place of coal plants up to a cost of \$50/tonne carbon) and through repowering existing coal-fired power plants so that they burn natural gas (again, up to a cost of \$50/tonne carbon). Because the new dispatch and the power plant conversions are up to \$50/tonne, a portion of the carbon reductions will be at less than this cost. The upper limit on these costs is thus \$50/tonne times 125 MtC/year = \$6 billion per year.

In addition, one needs to note that these measures increase demand for natural gas. The demand for natural gas in the AEO '97 business as usual case for 2010 is 30.2 trillion cubic feet

(Tcf). Our base case, which simulates a restructured utility industry, increases use of combined cycle power plants compared with AEO '97 by 1.3 Tcf per year in 2010. However, the efficiency case decreases natural gas use by 0.9 Tcf/year compared with AEO '97. This occurs because efficiency measures reduce demand for natural gas, as expected. Interestingly, the altered dispatch, when combined with efficiency measures in the high efficiency case, also reduces demand for natural gas by 0.9 Tcf/year compared with AEO '97. This occurs because of two countervailing factors that happen to balance in this case: (1) increased energy efficiency and further substitution of combined cycle gas plants for combustion turbines reduces natural gas demand while (2) substitution of additional natural gas for coal in the generation mix increases demand.

The roughly 50 MtC/year from repowering increases natural gas demand by 1.7 Tcf/year. This means that the high efficiency/low carbon case uses about 0.8 Tcf/year more natural gas than the AEO '97 (and 0.5 Tcf per year less than a restructured utility industry base case as we have estimated it). This is less than a 3% increase in natural gas demand. EIA model runs indicate that such an increase in natural gas demand would be expected to increase natural gas costs from \$0.15 - 0.20/million cubic feet (Mcf). This price increase has a small economic impact.

Finally, we obtain about 25 to 75 MtC/year from a variety of technologies: advanced turbine systems for cogeneration in industry, co-firing biomass and coal to produce electricity, fuel cells for buildings, low carbon technologies for cement making, biomass gasification, and advanced aluminum and cement production technologies as well as nuclear plant life extensions and expansion of hydropower. The text estimates that up to 75 MtC/year of carbon reductions could be achieved at less than \$50/tonne carbon. If these estimates are borne out, then the upper limit of these costs is \$4B/year in 2010 (since many of the technologies are estimated to produce savings below \$50/tonne carbon).

In short, the analysis suggests that the overall additional cost of the measures in the high efficiency/low carbon scenario are on the order of \$10B per year in 2010. To the extent that the energy efficiency measures cost less than new supply, the net cost of the stabilization case is reduced. On the other hand, implementation costs of energy efficiency and the other requirements to achieve rapid and widespread market acceptance of technologies will raise the cost of the scenarios, as discussed below

The realizability of the cases depends on many factors. In all cases, carbon reductions require the Nation to embark on an aggressive set of policies and programs, presumably in response to an international agreement on climate change or other events that result in a national determination to reduce growth of carbon emissions. In the case studied, we assume that an international trading regime for carbon has resulted in a domestic permit price of \$50/tonne carbon. Without some scheme that provides an incentive of this nature for switching from coal to natural gas, and for deploying other low carbon technologies, much of the carbon reductions in our case would not be possible.

Government policies and programs that encourage and/or require the adoption of energy efficiency technologies will be needed. Incentives will be needed for industry to increase energy efficiency investment. Additional private and public investments in energy efficiency and low carbon technology is necessary, not only to get some new technology into the market before 2010 but especially to have technology for the period after 2010. The transportation sector is especially dependent on early technological advances to achieve the scenario results in 2010.

There is no assurance that these and other driving forces will cause the scenarios we have described to take place. Our major conclusion is that the technology is available, at a cost that appears to be \$10 B per year or less, to achieve major reductions in carbon emissions by 2010. Efficiency alone can get us 30 to 50 % of the way to 1990 levels (from our expected base case

results) at negative or low technology costs. An important new finding is that a detailed analysis of the utility sector shows two significant ways that an additional 30% of the reductions at an estimated cost of \$50/tonne carbon¹: carbon-based dispatch and conversion of existing power plants from coal to natural gas. Finally, we identify additional technologies that could contribute up to 20% of the carbon reductions, also at a cost of up to \$50/tonne. In addition, 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 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 1

INTRODUCTION

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

The major greenhouse gases are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), ozone (O_3), nitrous oxide (N_2O), and a host of engineered chemicals such as chlorofluorocarbons (CFCs). CO_2 accounts for a majority of recent increases in the heat-trapping capacity of the atmosphere, with worldwide atmospheric concentrations of CO_2 increasing at about 0.5 percent annually. Of all the human activities that contribute to these increases, fossil fuel combustion is by far the largest, accounting for almost 60% of the greenhouse warming resulting from anthropogenic sources in recent years (NAS, 1992, Table 2.1, p. 8). Energy-efficient technologies reduce CO_2 emissions by displacing the need for fossil fuel combustion; this report limits its analysis to this single greenhouse gas. Further, because the global warming capacity of different greenhouse gases is commonly expressed in terms of million metric tons of carbon, this report quantifies the climate benefits of energy-efficient technologies in terms of reductions in metric tons of carbon emitted.¹

Analysis by a number of key climate and energy modelers indicates that significant research and development on greenhouse-friendly technologies – including energy-efficient technologies – is essential to achieving meaningful targets at affordable costs. As a result, climate change is becoming a major impetus for energy efficiency R&D programs and is likely to grow in importance in the future. By documenting the significant emissions reductions that past energy efficiency R&D can deliver by the year 2010, and by describing the potential for future research to lead to even greater efficiency gains, this report should be an important contributor to the development of a public response to climate change.

1.1 OBJECTIVES OF THE STUDY

The purposes of this study are fourfold:

- (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 technologies;
- (2) to document the costs and performance of the energy-efficient technologies that underpin a year 2010 scenario in which energy savings and carbon emissions reductions are achieved;

- (3) to also assess the carbon reduction potential by 2010 of selected low-carbon technologies and options for end users and for the electricity supply sector, and
- (4) 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 R&D (primarily) and renewable energy R&D (secondarily). The coverage of selected low-carbon end-use and electricity supply options was based in large measure on their potential to contribute significantly to stabilizing carbon emissions by 2010 at their 1990 level, which is one possible national target under discussion.

1.2 METHODOLOGY

1.2.1 Overview

To achieve these objectives, we started with the *Annual Energy Outlook 1997* (AEO '97) 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 either to accept them as is (which was the option chosen for buildings and industry), or to modify some of the assumptions and data and produce a modified "business-as-usual" scenario (which was the option chosen for transportation).

We then assembled existing information on 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 is 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.

We then estimated 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 two cases other than our "business as usual" case that we derived from AEO '97. We have termed the first the "efficiency" case. It assumes that the Nation increases its emphasis on energy efficiency through enhanced public- and private-sector efforts. This case was designed to be achievable without major changes in our way of doing business in energy. The "efficiency" case involves only cost-effective energy efficiency technology and assumes that not all cost-effective energy efficiency technologies will have been adopted by 2010 because of various market lags.

The other case, dubbed the "high efficiency/low carbon" case, assumes a greater commitment to reducing carbon emissions through federal policies and programs, strengthened state programs, and very active private sector involvement. This includes a focused national R&D effort to develop and transform markets for low-carbon energy options (e.g., biofuels for automobiles), and an increased willingness to pay to decrease carbon emissions.

The model runs for each of the three end-use sectors were not integrated and therefore may overstate the effects of technology penetration. In an integrated modelling effort, fuel prices might fall as consumption declines, resulting in less penetration of energy-conserving technologies. Alternatively, in forecasts that involve the creation of a permit price for carbon,

the price of some fuels could rise, thereby engendering greater investments in energy efficiency. Resource constraints simply did not allow the completion of an integrating analysis.

For one fuel – electricity – we examine the impact of the efficiency scenarios on prices and found no discernible impact. The same detailed assessment of the electricity supply system was conducted to estimate the carbon emissions that would be displaced under the efficiency scenarios. This analysis revealed 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 issue of 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 was identified as a key issue for study.

In addition to the work focusing on 2010, we peered beyond. Here our methodology is to focus on new technologies, materials, processes, manufacturing methods, and other R&D advances that promise to offer significant energy benefits by the year 2020, but where specific levels of market penetration, energy savings, and carbon reductions are difficult to forecast. Thus, instead of building scenarios we describe the technological innovations that could, if appropriate investments in R&D are made, form a basis for significant changes in the way we use energy. We believe that addressing the technologies that can be developed, and the R&D needed to do so, is the key to longer-term reductions in carbon emissions; a great deal more effort than we have expended is needed, however, to make quantitative predictions of what is likely to occur if the needed R&D is undertaken.

1.2.2 Time Frame

Analysis for all sectors focuses on two base years (1990 and 1997) against which future progress is benchmarked, and two target years (2010 and 2020) for assessing emissions reduction potential. Energy use and emissions for 1990 are reported because that year is the likely base year for any future, national greenhouse gas reduction targets.

Because it is the year in which this study is being conducted, 1997 is treated as a second base year. For this year, draft AEO '97 results will be used as the source for energy use by fuel and end-use sector.

As noted, the shorter target date – 2010 – is the year in which we quantitatively assess the reservoir of potential savings. The report examines a "snapshot" of energy use, by sector, in 2010. The increased use of energy-efficient technologies combined with the development of new technologies based on past R&D plus an invigorated R&D effort initiated in 1998 are needed to achieve our 2010 scenarios.

The analysis of 2020 highlights the likely post-2010 benefits of an intensified investment in energy efficiency R&D. It will capture the effects of technologies that may not be available for several 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.

1.2.3 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 addition, the buildings sector

presents a "frozen efficiency" baseline, for additional comparison purposes. While there is considerable variation in the methodologies used to estimate the energy savings and emissions reductions potential of each sector, the three sector chapters are consistent in their use of a combination of technology analysis and model-based forecasting, and each sector uses consistent conceptual definitions of the scenarios. Specifically, the buildings and transportation sector uses 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 input.

All of the scenarios described in this report use the AEO '97 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 AEO '97 forecast of growth in residential and commercial floorspace, the industrial sector uses the AEO '97 assumption of a 2.1 percent annual growth rate for manufacturing production, and the transportation sector uses the AEO '97 forecast of a 3.7 percent annual increase in air travel.

The scenarios for each sector also use the AEO '97 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 AEO '97, natural gas prices in the industrial, electricity, and transportation sectors increase throughout the forecast period; prices to residential and commercial sectors decrease significantly. Between 1995 and 2010, the average price of electricity is projected to decline by 0.6 percent 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 Energy Information Administration (1996b).

As in the AEO '97 reference case, each of the scenarios is completed at the national level. Thus, regional variations in population and economic growth are not considered, nor are regional differences in fuel prices. (The few exceptions to this are the case studies of market opportunities for fuel cell cogeneration in buildings and for ethanol produced from cellulose as a transportation fuel.) As a result, our analyses have undoubtedly overlooked the possible development of regional niche markets for advanced energy technologies. We assume, however, that our national results would not change significantly with the inclusion of such regional developments.

"Frozen Efficiency" Baseline. This case assumes that energy-consuming equipment and systems existing in the year 1997 remain at the same efficiency until they are retired. Further, this equipment and these systems retire over the 1997-2010 period at a rate determined by standard equipment lifetimes. It assumes that all new equipment built after 1997 remains at the efficiency of new devices in the year 1997. The frozen efficiency baseline will provide an upper bound to likely demand (under the economic assumptions applied to all the cases), since 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 are 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 largely because an important purpose of this study is to explore the impacts of technology change. Also, the case is not necessarily divorced from reality: in the era of low energy prices preceeding the oil embargo of 1973-74, the energy efficiency of many household, transportation, and industrial technologies changed very little. The primary purpose of this case is to provide a construct for the reader to compare with the

other cases to highlight the effect of technology change. As noted, this case has only been developed for the buildings sector.

"Business-as-Usual" Case. The business-as-usual 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 DOE and EPA R&D and implementation programs 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, each sector begins with the AEO '97 reference case, and modifies parts of it as needed to reflect the authors' best judgement of how the future will likely evolve under prevailing levels of public support for R&D and market transformation. For example, in the transportation sector, the AEO '97 reference case forecasts that the efficiency of passenger cars will increase from 27.5 MPG in 1997 to 31.5 MPG in 2010. The authors of this report's transportation analysis concluded that such improvements were unlikely in the absence of increases in real gasoline prices and hence assumed in their revised reference case that the MPG performance of light-duty vehicles in 2010 will be unchanged from 1997.

"Efficiency" Case. The efficiency case describes the realistic 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, economic conditions, or exogenous events that could precipitate such changes. Instead, we examine the potential for technology-based energy and carbon reductions, assuming that these technologies have become attractive to technology manufacturers and distributors and to the consuming public and business community.

To be attractive to these audiences, 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. 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 environmental benefits. But the technology must be cost-effective from the consumer's perspective for it to be included in the efficiency case. 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, Jorgenson, Krugman, Nordhaus, Solow, et al., 1997).

The efficiency case assumes (1) better technology and (2) higher penetration rates for energy efficiency technologies than the business-as-usual case.

- (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 market transformation programs that remove or reduce market failures which inhibit the use of energy-efficient systems. Market transformation programs, for instance, could eliminate misplaced incentives or reduce perceived risks by providing more reliable information about the cost savings that advanced efficiency technologies can deliver. Risk can also be reduced through various forms of risk sharing. 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. Such changes in capital markets and consumer decision-making could also occur as the result of greater revealed preferences for the public benefits of "green" technologies.

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 (U.S. Department of Energy, 1996).

"High Efficiency/Low-Carbon" Case. The high efficiency/low carbon 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 high efficiency/low carbon case, a policy is announced in 2000 and its restrictions are phased-in over a several-year period, so that the policy would take full effect in 2010. The permit price for carbon would presumably rise steadily through 2010. Thus we have multiple factors affecting consumer and business behavior, including the "announcement effect" of the agreement (i.e., actions that take place because the climate change policy undertaken produces anticipatable increases in the future price of energy); the actual increases over time in the permit price of carbon (which we are modeling as averaging around \$50 a 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 psychology that would result from an international treaty and national commitment to stabilize greenhouse gases. The latter change in psychology would—assuming the IPCC is correct—be increasingly spurred over time by growing evidence that the climate is actually changing.

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.

1.2.4 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 1.1). 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 efficiencies 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% 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 industrial sector assumes a Capital Recovery Factor (CRF) of 15%. Thus, to be considered cost effective in this sector, an investment must pay back in no more than approximately 7 years.
- The transportation sector uses a 7% discount rate, but it is applied only to the first 5 years of operation, even though the expected lifetime of a vehicle may be much longer. This 5-year period is meant to reflect the realities of purchase behavior in this sector, and results in decisions being based on considerably less than the full life cycle of benefits.

1.2.5 What the Study Does Not Do

This report does not describe in detail the policies that might be implemented to achieve higher penetrations of energy efficiency technologies. [Reviews of a wide range of possible policy options can be found in several recent publications (Office of Technology Assessment, 1991; National Academy of Sciences, 1992; and U.S. Department of Energy, 1996).] 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 energy efficiency policies to work. Without the technologies, policies to reduce greenhouse gas emissions will be very costly. Indeed, carbon stabilization could be considerably less costly 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. Additional work will be needed to further refine our analysis of technologies, to improve understanding of what is needed to achieve market penetration of the technologies, and to assess costs and benefits of policies.

Table 1.1 Conceptual and Operational Definitions of Scenarios for 2010

Scenario/ Definition	Business-as-Usual (BAU)	Efficiency	High Efficiency/ Low Carbon
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.	Realistic 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 based on a greater commitment to reduce carbon emissions resulting from actions that might include the creation of a market value for carbon of approximately \$50 per ton.
Operational Definitions:			
Buildings	AEO '97 reference case developed using the NEMS model. ^a	35% of the difference in total energy savings between the BAU and maximum cost-effective efficiency potential. ^b	65% of the difference in total energy savings between the BAU and maximum cost-effective efficiency potential.
Industry	AEO '97 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	AEO '97 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 maximum cost-effective potential savings 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.

A second reason for focusing on technologies is our belief that the role of R&D on energy-efficiency and low-carbon technologies as a means to deal with climate change and other environmental impacts has been inadequately recognized. The statement in the previous paragraph is critical to this issue: 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. While this statement may appear evident, there is virtually no recent in-depth analysis of what R&D is needed and what impacts of the R&D might be expected. We intend this report to provide a serious initial assessment of this important topic.

1.3 OVERVIEW OF THE REPORT

Chapter 2 sets the stage for the remainder of the report. It describes historical energy trends, both at the national level and by sector, as a backdrop for assessing energy consumption forecasts. It also discusses the government's role in energy efficiency RD&D, including the rationale for government support and some evidence of past energy efficiency technology successes that benefitted 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 forecasts with and without a strong efficiency push, focusing on the year 2010, and including comparisons with the AEO projections from the National Energy Modeling System and other forecasts;
- (2) preparation of illustrative energy supply curves (or comparable documentation of the cost and performance of energy efficiency 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 labelled Appendix C (buildings), D (industry), and E (transportation).

Chapter 6 analyzes the electricity sector to forecast the effect of electricity and demand savings in the year 2010 on CO₂ emissions from power plants. It also assesses the impact of a \$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 revealed 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 issue of, the possible early retirement of some coal-fired plants, and the upgrading/repowering of existing plants was identified as a key issue for Chapter 7.

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

Chapter 8 summarizes the report's findings. It begins by aggregating the results of the 2010 efficiency scenarios to estimate the total energy savings and carbon reduction benefits that can accrue from an invigorated national commitment to energy efficiency RD&D. Next it highlights the key findings of each scenario, by sector. The chapter then summarizes the potential for sustained energy efficiency and renewable energy RD&D to generate carbon reduction benefits over the next quarter century. The primary focus of this report is on the ability of energy

efficiency technologies to reduce carbon emissions by the year 2010; however, it is recognized that additional technology solutions will be needed to enable a sustainable energy future well into the 21st century. Thus, Chapter 8 includes a discussion of some of the low-carbon end-use and electricity supply-side options that could help bring the Nation's carbon emissions in 2010 down to its emissions level in 1990.

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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) 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. (2) Carbon units are more convenient for comparisons with data on fuel consumption and carbon sequestration (Energy Information Administration, 1996a).

CHAPTER 2

BACKGROUND

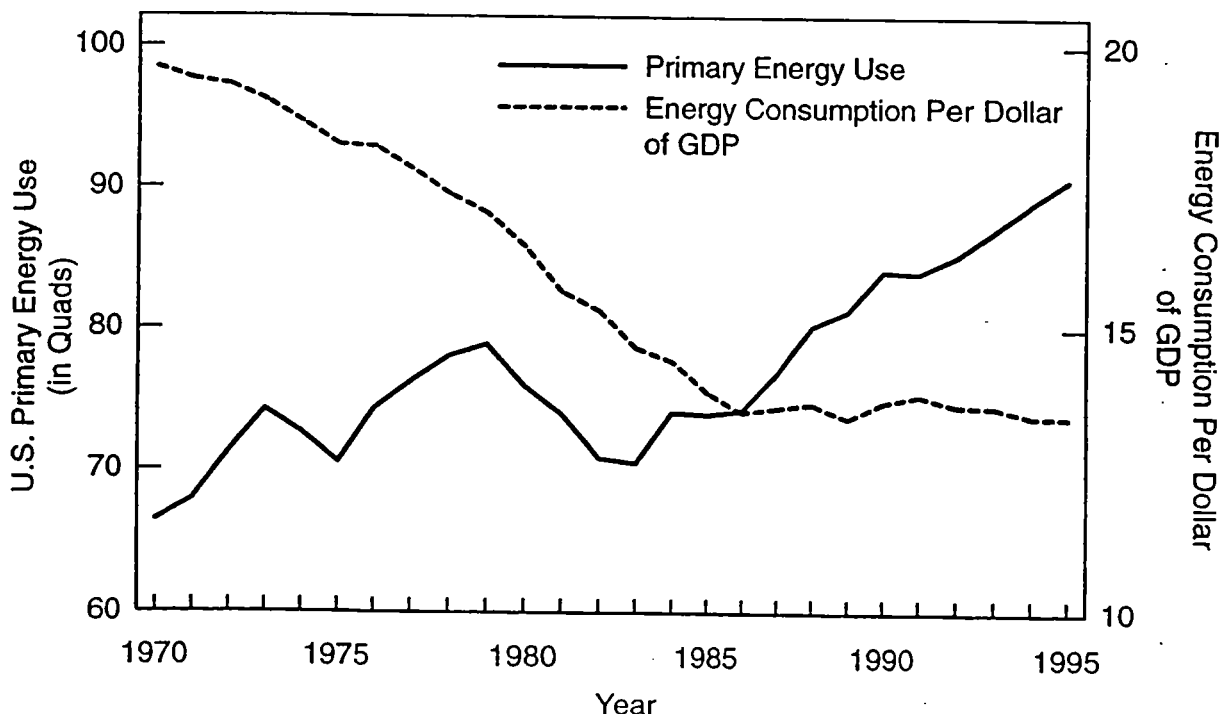
2.1 HISTORICAL ENERGY TRENDS

2.1.1 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%.¹ 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. Although one-third of the freeze in energy use during this period was due to structural changes such as declines in energy-intensive industry and increases in the service sector, two-thirds was due to increases in energy efficiency (U.S. Department of Energy, 1995).

Figure 2.1 Energy Consumption Per Dollar of Gross Domestic Product: 1973-1997



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

that the U.S. economy improved its energy productivity can be quantified by examining the relationship between total energy consumption and gross domestic product (GDP). 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 (EIA, 1996, p. 17). DOE estimates that the country is saving \$150 to \$200 billion annually as a result of these improvements.

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. Consumer preferences for energy-efficient appliances, houses, and cars can slow the switch to less energy-efficient products, and technological developments can improve both the energy efficiency and the performance of the product, effectively reducing the cost of energy-efficient purchases. Demand for energy-efficient products is also strengthened by factors such as environmental concerns.

2.1.2 Sectoral Trends

Each end-use sector functions differently in the U.S. energy marketplace. One of the reasons for these differences is the unique marketplace 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. Information gaps prevent the 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. Industrial buyers select the technologies that are used in the production process. 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. 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 (U.S. Department of Energy, 1996).

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, by driving less and by adjusting thermostat settings. But transportation is relatively fuel inflexible, being primarily dependent upon petroleum, while the buildings and industrial sectors have greater fuel flexibility.

Finally, each of the sectors is distinct in terms of the primary societal benefits from improved energy efficiencies. Improving the efficiency of transportation is essential to improving air quality and making the economy less dependent on imported oil. Improving the efficiency of the industrial sector is essential to economic competitiveness and pollution prevention. Energy-efficiency improvements in the buildings sector are especially critical to reducing greenhouse gas emissions, since most of the energy consumed in buildings comes from the burning of fossil fuels.

Such differences make analysis by end-use sector essential for understanding the U.S. energy picture as a whole.

Table 2.1 presents the primary energy consumed by the buildings, industry, and transportation sectors between 1973 and 1997. It shows that significant sectoral differences are hidden by national-level statistics. For instance, during the 1973-86 period when the country's primary energy use was steady at 74 quads, each of the sectors showed significant shifts in energy use. Specifically, energy use in buildings increased by 2.7 quads and in transportation by 2.2 quads, but industry experienced a compensating decline of 4.9 quads.

Table 2.1 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 Energy Information Administration (1996a, Table 2.1, p. 39). Energy use estimates for 1997 come from Energy Information Administration (1996b).

Over the entire period from 1973 to 1997, energy use in buildings increased 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%). The growth in buildings and transportation has been relatively steady, at less than 1 percent per year from 1973 - 1986, and between 1.5 and 2.6 percent per year from 1986 to 1997 - with an average of 1.7 percent - as shown in Table 2.2. 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 percent annual growth for the 13 years of declining prices), an increase of 2.7 percent per year from 1986 to 1995, and a 1.8 percent per year decline from 1995 to 1997. The average annual growth rate for industry, when calculated over more than a decade, was -1.3 percent during rising prices and +1.3 percent during declining or constant real prices.

Table 2.2 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 2.3 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 2.3 Carbon Emissions from Fossil Energy Consumption: 1973 to 1997

	1973	1986	1990	1995	1997
Carbon emissions from energy in million metric tons	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 Energy Information Administration (1996c, Table 6, p. 16), and for 1995 are from Energy Information Administration (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.

2.2 THE GOVERNMENT'S ROLE IN ENERGY EFFICIENCY RD&D

2.2.1 Rationale for Government Support

Few would disagree 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 RD&D process is justified. First is the situation where the potential aggregate benefits to 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 RD&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. The third situation occurs when the public sector is the primary consumer of the results of the RD&D. This is characteristic, for instance, of much defense and crime prevention research. *2nd situation*

Based on these three justifications, the rationale for government support of energy efficiency RD&D is strong. Much energy efficiency 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 efficiency also offer substantial public benefits that cannot be fully captured by private entities. Specifically, energy efficiency improves energy security by reducing the nation's reliance on foreign sources of oil; it leads to reductions in waste streams; and it reduces 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 efficiency R&D will also apply.

Given recent trends in corporate R&D funding, one could argue that the need for energy efficiency R&D support is increasing. 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 percent of overall company R&D spending, while basic research has dropped to just 2 percent. In addition, corporate investments in energy R&D, in particular, are down significantly (U.S. Department of Energy/Office of Policy, 1996, p. 2).

2.2.2 Past RD&D Successes

Some indication of the cost-effectiveness of energy efficiency RD&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 energy savings of approximately \$28 billion (1996-\$) and annual emissions reductions of 16 million metric tons of carbon equivalents (Table 2.4).

Table 2.4 Energy Savings and Carbon Reductions from Five Energy-Efficient Technologies Developed with DOE Funding

Energy-Efficient Technology	Cumulative Energy Savings Thru 1996, in Billions of \$-1996	Annual Carbon Reductions in 1996, in Million Metric Tons of Carbon Equivalent
• Building Design Software (energy savings directly linked to DOE)	11.0	8
• Refrigerator Compressor (energy savings directly linked to DOE)	6.0	3
• Electronic Ballast (energy savings of ballasts in use)	3.7	1
• Flame Retention Head Oil Burner (consumer savings from market acceleration)	5.0	3
• Advanced Windows (savings of windows in use)	3.0	1
Totals	28	16

Note: Savings for the refrigerator compressor and flame retention head oil burner are through 1996 only; the remainder are savings over the lives of investments made through 1996.

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).

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¹ 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—called 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 (National Academy of Sciences, 1992, p. 3).

CHAPTER 3

THE BUILDINGS SECTOR

3.1 INTRODUCTION

Energy is used in buildings to provide a variety of services to users 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 for delivering all energy services in buildings (such as cold food, lighted offices, and warm houses) was over \$200 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 (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 2010¹. 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. 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, see U.S. DOE (1995b).

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 3.6 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 reported 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 1 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 result 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 (energy end-use per household or per unit floor area) for all end uses for 1997 and, in our initial assessment, use the factors from U.S. DOE *Annual Energy Outlook* (AEO '97) to calculate expected values in 2010 to establish baseline values (U.S. DOE, 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. In a few cases, we adjust the AEO '97 values for energy intensity in 1997 or 2010 based on independent analysis.

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 and future demands for energy services by end-use.

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, efficiency, and high efficiency/low carbon. 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 by the U.S. Department of Energy (U.S. EIA, 1996).

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 building shells and equipment. This maximum efficiency potential was calculated as the difference between the energy intensity of the most energy-efficient technology currently available and cost-effective, and the energy intensity of new equipment in 1997. The maximum cost effective efficiency improvements are based on detailed studies; no measures were included with a cost of conserved energy greater than the average cost of purchased fuel or electricity.² For comparative purposes, we have also analyzed a case in which the efficiency of all new equipment and building shell measures is kept at 1997 levels of new products (frozen efficiency case).

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

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

End Use/Fuel	1990	1997	2010		
			Business-as-Usual Case	Efficiency Case	High Efficiency/Low Carbon Case
Residential:					
Electricity	10.2	11.9	13.0	12.0 (7.1%)	11.0 (15.3%)
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%)	18.2 (10.7%)
Commercial:					
Electricity	9.4	10.6	11.4	10.7 (6.0%)	9.9 (13.1%)
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%)	13.7 (11.9%)
Sector Total:					
Electricity	19.7	22.5	24.3	22.7 (6.6%)	20.9 (14.3%)
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%)	32.0 (11.2%)

Note: numbers may not add to the totals due to rounding. Numbers in parentheses represent percent reductions from the business-as-usual (BAU) case.

Why is 90-97 Δ > 97-10BAU Δ ?
 is econ growth expected to slow, or is
 AEEI outstripping econ growth?

Table 3.2 Carbon Emissions in the Buildings Sector (in million metric tons): 1990-2010

End Use/Fuel	1990	1997	2010		
			Business-as-Usual Case	Efficiency Case	High Efficiency/Low Carbon Case
Residential:					
Electricity	162	183	213	202 (5.4%)	167 (21.9%)*
Fossil Fuels	91	102	106	104 (1.5%)	102 (2.9%)
Subtotal	253	285	319	306 (4.1%)	269 (15.6%)
Commercial:					
Electricity	150	163	187	178 (4.7%)	151 (19.2%)*
Fossil Fuels	59	62	65	62 (4.5%)	59 (8.4%)
Subtotal	209	225	252	240 (4.7%)	211 (16.4%)
Sector Total:					
Electricity	312	346	401	380 (5.1%)	318 (20.6%)*
Fossil Fuels	150	164	170	166 (2.7%)	162 (5.0%)
Total	462	511	571	546 (4.4%)	480 (16.0%)

Note: Numbers may not add to the totals due to rounding. 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/metric ton of carbon.

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 after a review of program experience (Brown 1993) and a judgmental assessment of how energy service markets would respond to policies and programs associated with aggressive commitments to reduce carbon emissions. We began with the Brown's 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 would push the 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 US DOE (1995b), 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 g C/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 increases to 207 gC/kWh because it is assumed in this case that a carbon charge of \$50/metric ton of carbon is implemented (in addition to the other non-price policies) that causes changes on the supply side as well as promoting demand-side programs to capture 65% of the potential savings. Some coal plants are retired in this case, which increases the marginal carbon savings factor significantly.

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.

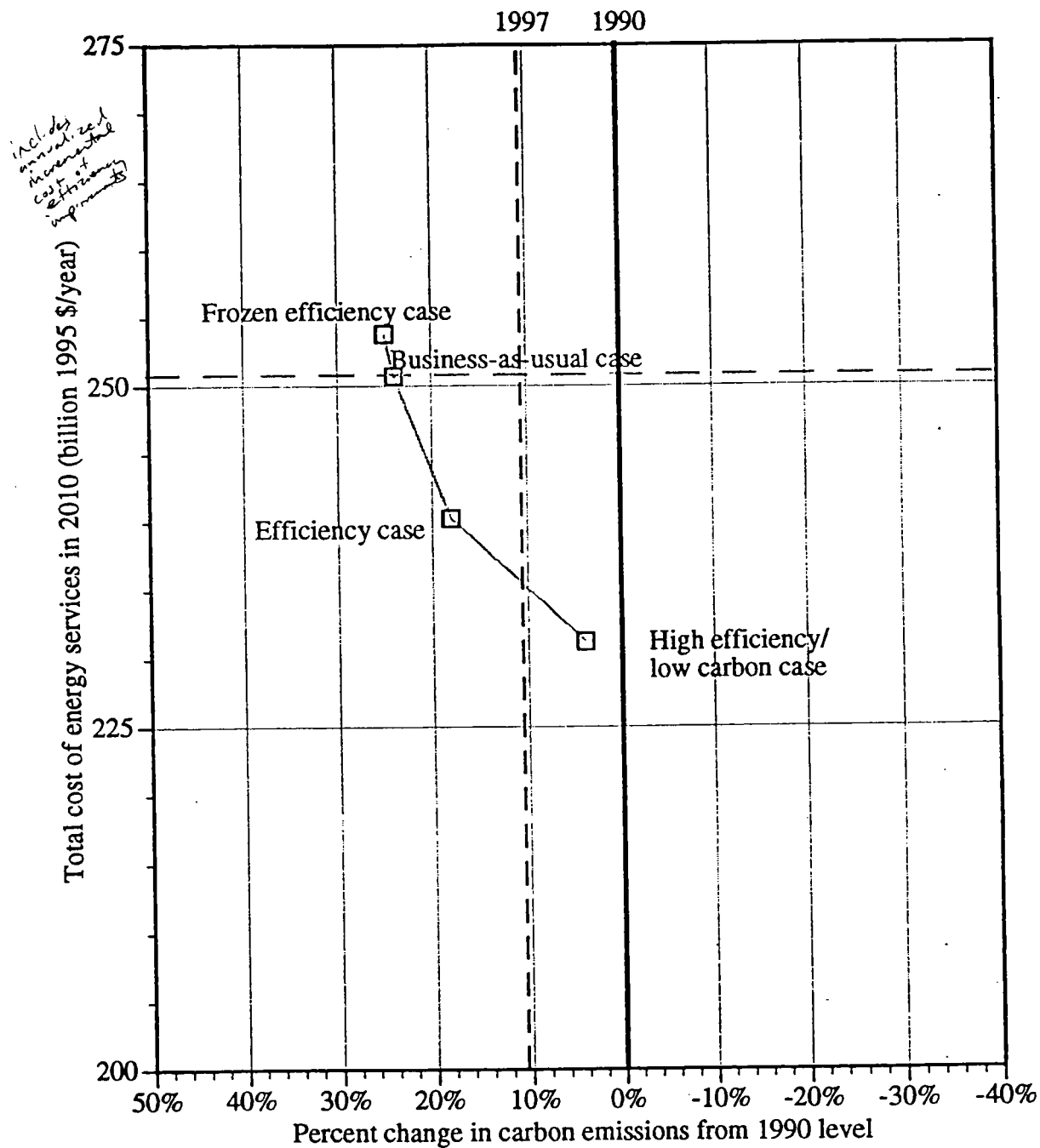
The format of Figure 3.1 is based on the graphs first introduced by Krause et al. (1993) and further developed in Krause et al. (1995). On the X-axis is the percent change in carbon emissions from 1990 levels. On the Y-axis is total cost of energy services in 2010, expressed on an annual basis. This cost includes the annualized incremental cost of efficiency improvements beyond the business-as-usual case plus the cost of electricity and fuel purchases.

**Table 3.3 Annual Total Cost of Energy Services in the Buildings Sector
(in 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	\$14
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 annual 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).

Figure 3.1 Results of the Business-As-Usual, Efficiency, and High Efficiency/Low Carbon Scenarios for the Buildings Sector



1990 US buildings sector C emissions = 462 Mt C

1997 US buildings sector C emissions = 511 Mt C

Figure 3.2 Residential Sector Energy Use and Carbon Emissions in 1997 and 2010 by End-Use for the Business-As-Usual Scenario⁵

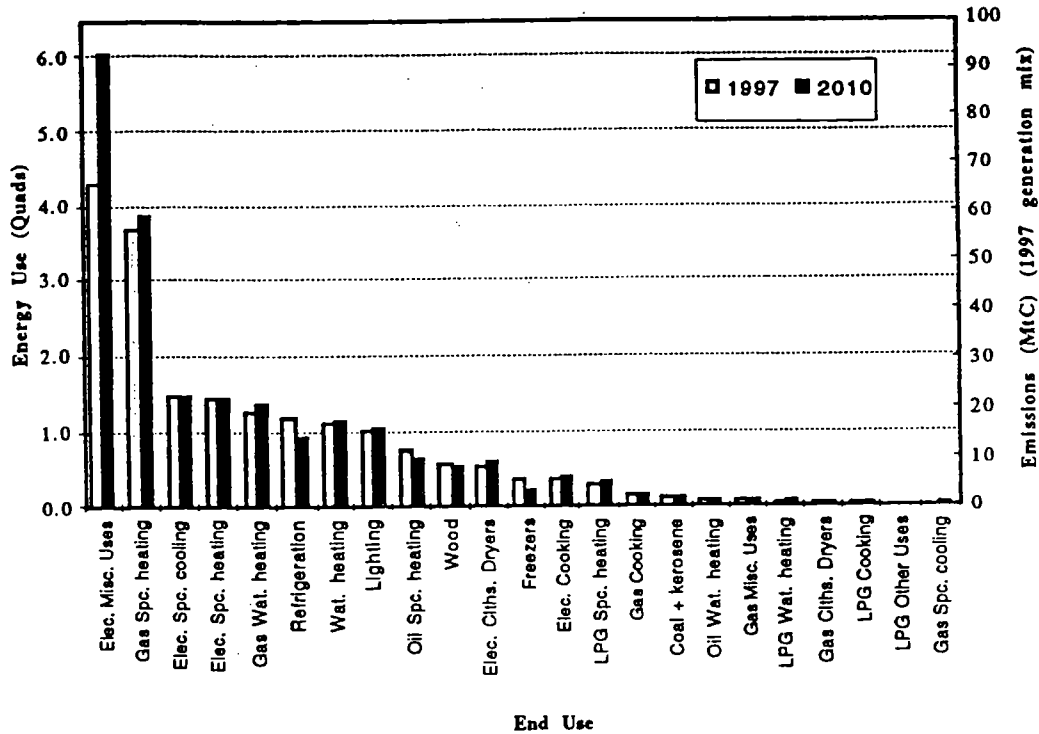
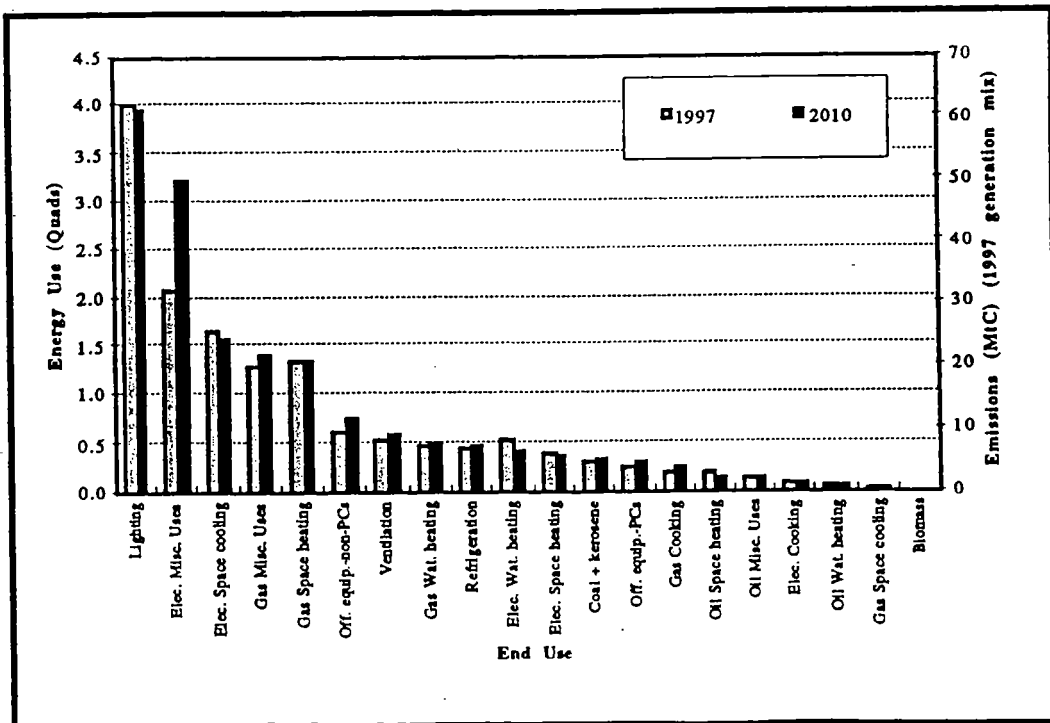


Figure 3.3 Commercial Sector Energy Use and Carbon Emissions in 1997 and 2010 by End-Use for the Business-As-Usual Scenario



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 sector. 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) while 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). The lower rate of increase in carbon emissions in the business-as-usual case reflects improvements in both energy supply and demand technology as well as changes in the fuel mix used to produce electricity. Since 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 BAU 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 13% increase from 1990 and 1997, respectively). The increase in emissions in this sector is due to moderate growth in residential building and equipment/appliance stock coupled with substantial growth in miscellaneous energy use.⁴ Emissions from the rise in miscellaneous energy use grow nearly four times as fast as the residential sector as a whole, resulting in the share of miscellaneous energy use jumping from 23% in 1997 to 30% in 2010. 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, energy use in the business-as-usual scenario is projected to grow by 18% from 1990 and 11% 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 8% from 1997 to 2010 (209 MtC in 1990 and 225 MtC in 1997 to 252 MtC in 2010). Similar to the residential sector, miscellaneous energy end uses such as motors, pumps, and fans are expected to increase from 18% of total commercial energy use in 1997 to 23% 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. 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 6.5% in 2010. The greatest increases in energy efficiency in the commercial sector come from continuing improvements in space conditioning (due to improved shells and equipment) and water heating systems. Commercial sector energy use and carbon emissions in 1997 and 2010 are shown in Figure 3.3 below.

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 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 compared the energy use and incremental cost to new 1997 equipment for that end use to calculate the potential reduction in energy intensity 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, significant savings potential exists for many end-uses in the residential and commercial sectors, compared to 1997 new equipment.

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 depend 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 reflects 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 even 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.

The difference in energy demand between the maximum cost-effective case and the business-as-usual scenario for all buildings is 6.5 quadrillion Btu/year 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 is the projected savings in 2010 in TWh, and on the y-axis is the cost of conserved electricity (CCE) in 1995 cents/kWh. Total savings in this scenario is about 16% of baseline electricity use. The most cost-effective savings comes from commercial lighting, which has a negative net CCE because of the labor savings associated with the replacement of incandescent A-lamps with longer-lived halogen IR and compact fluorescent lamps. The costs of savings in other end-uses range from 1.4 cents/kWh to 4.5 cents per kWh.

Figure 3.4: Electricity savings by end-use

Figure 3.5: Natural gas savings by end-use

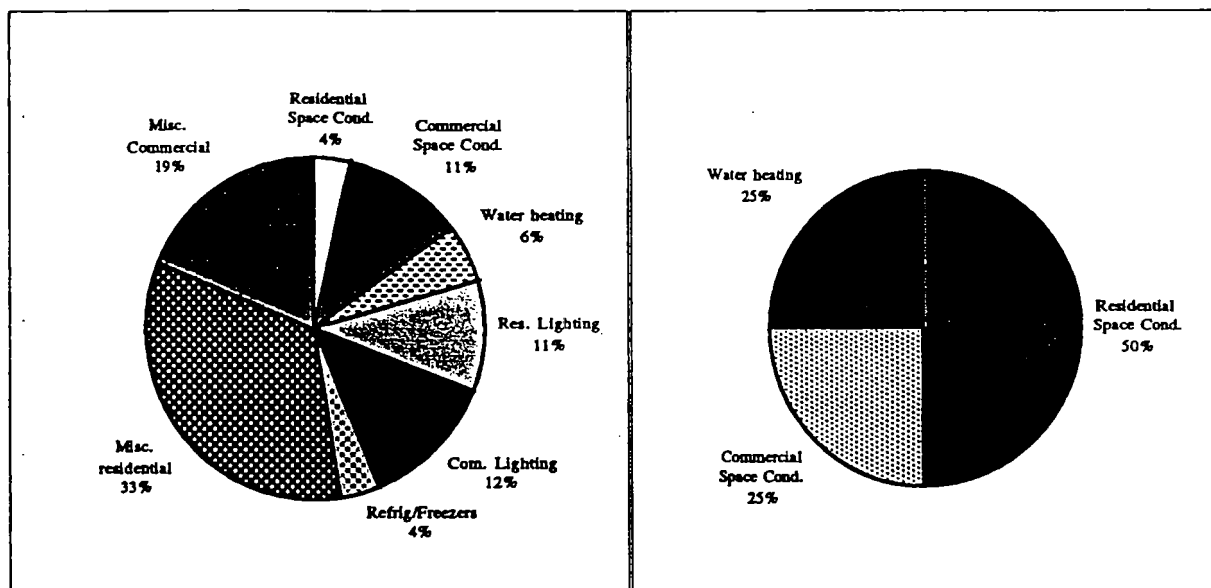
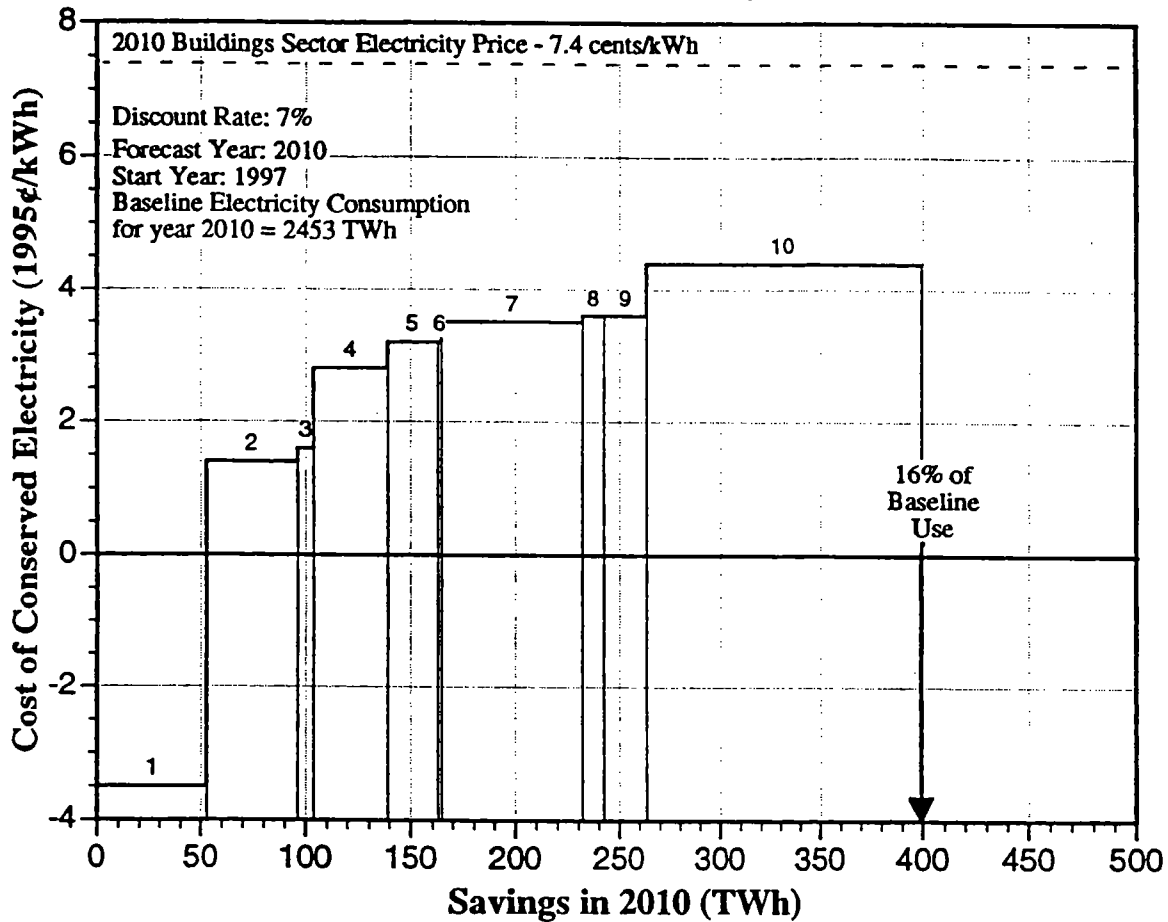


Figure 3.6: Electricity Supply Curve By Enduse for Buildings in 2010, High Efficiency/Low Carbon Case



- | | |
|----------------------------------|--|
| 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 |

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 cap and trade, energy efficiency standards, and information programs.

In the efficiency scenario, 2010 energy use drops to 34.0 Quads while carbon emissions decline to 546 MtC. In this scenario, the reduction in total annual energy services cost is \$11 billion per year below the business-as-usual scenario, reflecting the fact that the decrease in energy expenditures due to 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 following implementation of a vigorous effort to reduce energy use and carbon emissions.

Under a more rigorous high efficiency/low carbon scenario, 2010 energy use and carbon emissions drop further, to 31.6 Quads and 480 MtC respectively at a total cost savings of \$20 billion per year below the business-as-usual scenario. Annualized capital costs increase by \$7 billion over the costs in the efficiency case, but annual additional bill savings are about \$15B.

3.3.5 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. Based on penetration rates developed by Arthur D. Little, total installed electrical capacity from such fuel cells (given an aggressive R&D and commercialization effort) could total 5 gigawatts by 2010. As described in Table C-2.7 in Appendix C-2, implementation of this technology (or some combination of fuel cells and small advanced gas turbines in buildings) could result in primary energy savings beyond the high efficiency/low carbon scenario of about 0.4 Quads, and additional carbon savings of about 7 MtC. A more conservative forecast for the same scenario might be 4 MtC.

3.4 RD&D POTENTIAL FOR ADVANCED TECHNOLOGIES IN 2020⁶

To the casual observer, buildings in the year 2020 may look much like the buildings of today (Smith and Rivera, 1989). In part that is because Americans prefer familiar forms for their buildings and in part because new buildings amount to only 2 to 3 percent of the existing building stock in any given year. Nearly 90 percent of the residential buildings that existed in 1997, and 80 percent of the commercial buildings, 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 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 significant 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. Significant investments in RD&D will be needed to produce energy-efficient technology alternatives that building owners will be motivated to purchase. 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.

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 radically new 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
- self-powered buildings.

In each area, thought must be given not only to the energy-efficient technology and to 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 programming, design, construction, commissioning, financing, operation, renovation, reuse, and disposal of buildings 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 work for single-family homes, low-rise, multi-family construction, and repetitious commercial buildings (restaurants, schools, 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 cannot be afforded 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 commercial buildings. Modular and easily installed heating, ventilating, and air-conditioning 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 material, 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: mixed paper waste in lieu of pure newsprint to cellulose insulation and drywall, wood wastes to engineered structural members as opposed to only particle board, flyash to lightweight masonry products as opposed to site fill material, corrugated paper to structural insulating panels, and 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's 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, commissioning, and creating calibrated computer models to verify that actual 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, allowing future designs to benefit from lessons learned in past buildings.

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.

3.4.1.2 Climate-Specific Design and Adaptive Envelopes

Advanced designs and technologies that intelligently integrate the performance of buildings to 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-E glazings 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 outperforms a highly insulated wall even on northern exposures in winter, by enabling the diffuse gain to exceed the winter thermal losses.

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

Research on insulation to date 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, 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, design and construction guidance is needed for such thermal mass strategies to achieve their technical potential by identifying 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 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. Self-drying roofs also significantly reduce the cost of repairing, replacing, and disposing of roofs.

The hot roofs and pavements of urban environments raise ambient air temperatures by several degrees Fahrenheit, which in turn increases air conditioning requirements and the production of ozone, which is the main ingredient of smog and a major irritant to eyes and lungs. Urban heat islands can be dissipated by using lighter colors for roofs and pavements, and by strategically planting trees. Reducing heat islands in warm climates can significantly decrease the cooling loads of buildings (Rosenfeld, et al., 1997). Advanced roofing, paving, and coating technologies are needed to capitalize on these opportunities.

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.

3.4.1.3 Multi-Functional Equipment and Integrated System Design

During the period through 2010, the efficiencies of heating, cooling, and ventilating 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 which 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 but 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 which 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 beyond this level of performance as a single-function appliance appears not to be cost effective in the near term and beyond if real energy prices continue to decrease.

Opportunities continue to exist in 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 are needed 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 since 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 the HVAC systems to reduce indoor concentrations of airborne particles such as pollen, other allergens, and infectious agents which 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 which can control space humidity and temperature independent of each other. Research on combined systems based on desiccants to control humidity and vapor compression air conditioning for space temperature control 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, multistage 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. Also 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. This usage could be reduced by over 50% by 2020 with equal or improved health, comfort and productivity by the development and intelligent use of more efficient technology and design.

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 \$10B/year for new lighting equipment but \$40B/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) the light or ballast efficacy, 2) the fixture efficiency, 3) the spatial task efficiency, and 4) the 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 over the last 20 years modestly to a range of 80-120 lumens/watt, which is still well below the theoretical limit of 220 lumens per watt for white light. The industry is exploring new electrodeless solutions at both small sizes (10-100 watts) as well as in the kilowatt range. Large lamps such as the sulfur lamp have demonstrated almost 150 lumens per watt 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 cheaper, 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, with the goal of achieving two visible light photons for each UV photon.

By 2020 there will be many new CFL options with smaller size, better color rendition, higher luminous output, and dimmability that might fill 30-50% of those sockets. But there will still be a tremendous market need for a long life, very low cost 30-40 l/w 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). Small lamps are also easier to integrate with optically efficient fixtures or fiber optics.

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, multilevel 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 ECMS 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 but 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 slash 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 heating, cooling, ventilation, 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, plus property and facilities management.

In appliances like 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.

Development of the right mix of sensors, controls, and communications equipment needs to adjust to developments for "plug load" devices in buildings. The AEO '97 (Energy Information Administration, 1996) predicts that by 2015 the energy use in these devices will account for more than 20 percent of the total energy use in the residential sector. At the same time, advances in office equipment performance could mitigate potential increases in many parts of the commercial sector (Komor 1996). Novel control strategies that promote energy efficiency can influence this scenario for the future in a major way.

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 and that market will have matured by 2020 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.

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. No other system identified to date can generate electricity, provide heat and hot water, has fuel flexibility, is modular, has quiet operation, is a non-polluter, and has an overall conversion efficiency potential of 80% or better (Fiskum, 1997). These devices will be preferred to gas turbines because of their lack of moving parts and inherently quiet operation. 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 \$3,000/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 \$7,000/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

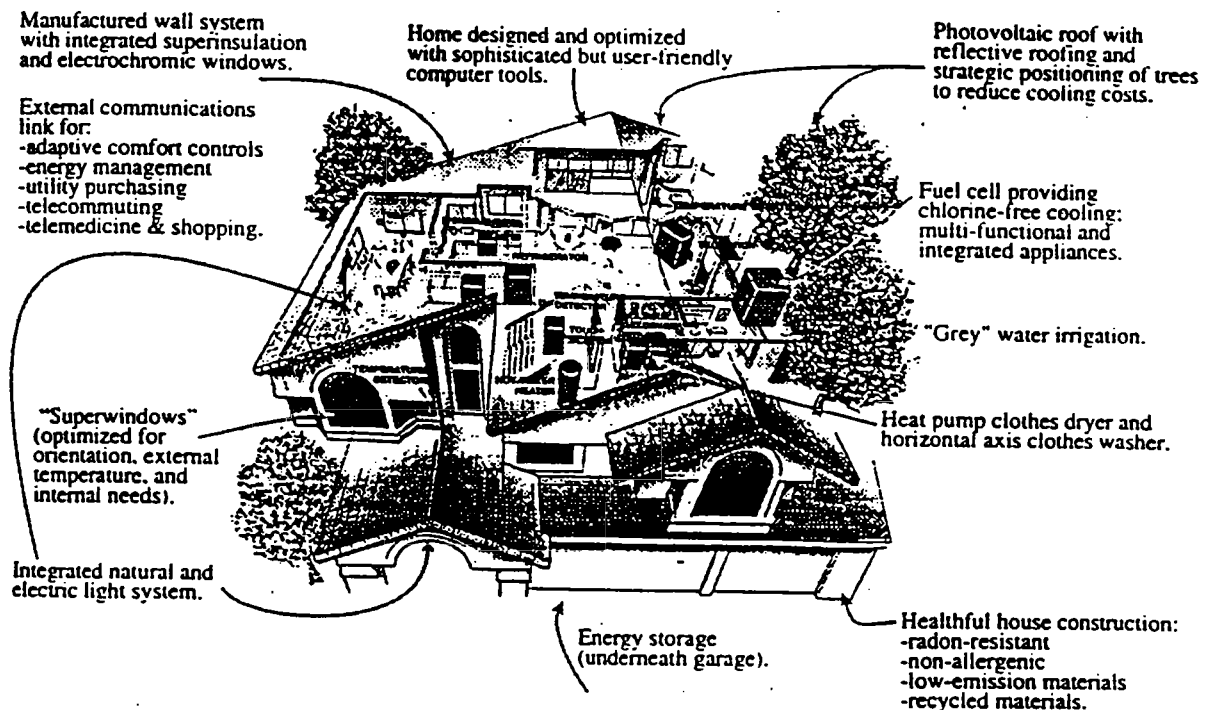
By the year 2020, a vigorous RD&D program could produce many advanced technologies that together will greatly reduce the average annual energy budgets of American families. The "Best Practice" home of the year 2020 is defined as a home that employs those energy technologies that are predicted to have 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

"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 photovoltaic 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 US. 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.

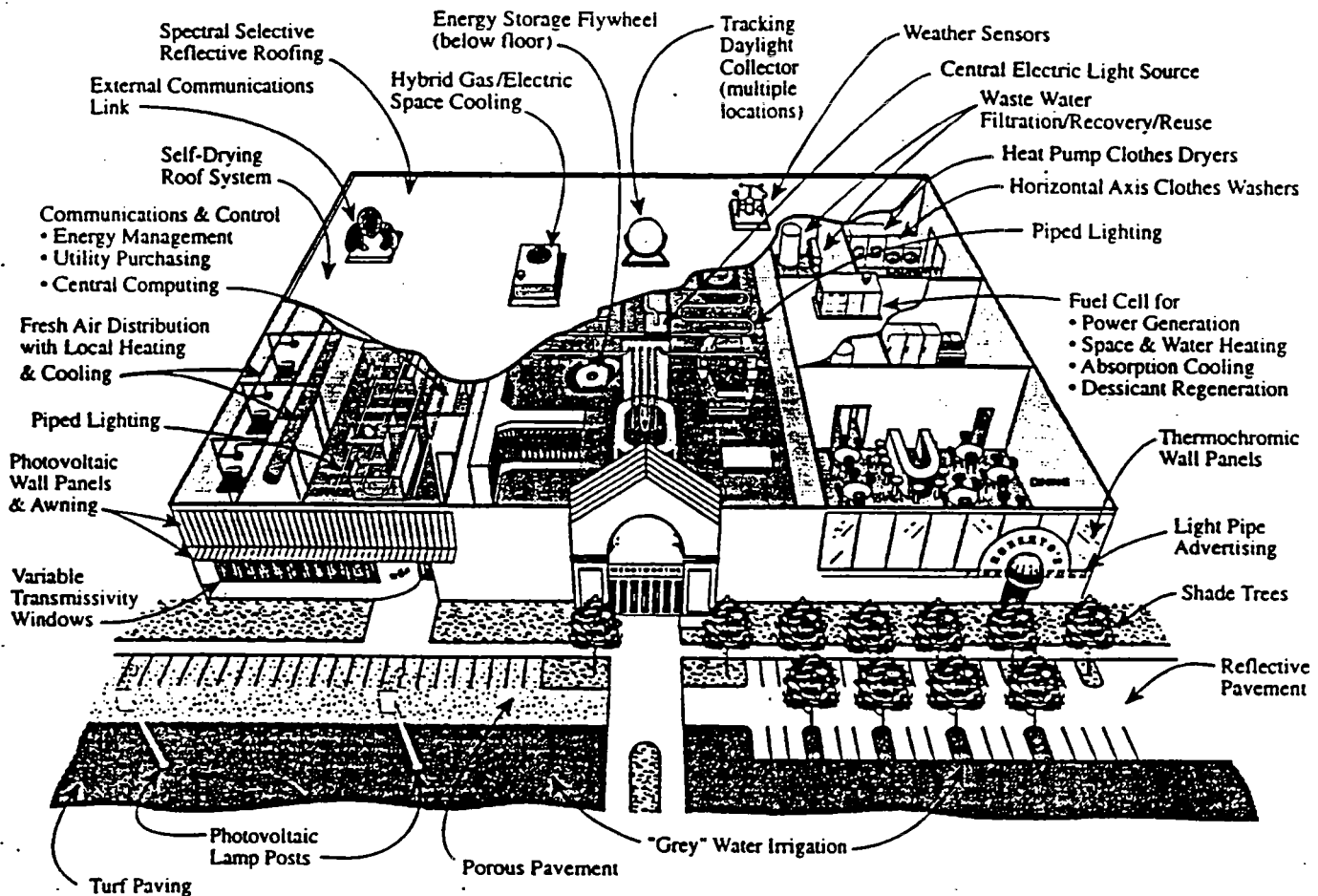
Commercial buildings will continue to look similar to those existing today. The primary change will be in the "mix" of these facilities as the advances in electronic information dissemination reduce the need for physical interaction, and therefore the size, of some commercial buildings. Some "traditional" 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.

The state-of-the-practice commercial buildings will be heavily reliant on manufactured components for its construction. One-of-a-kind structures may continue to have many site-built components, but repetitious commercial buildings (e.g., franchise restaurants and retail stores), will consist primarily of 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.

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

Composite Commercial Building-2020



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 re-circulated air will be minimized. Individual control 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. The state-of-the-practice commercial building 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 (CFCs) refrigerants will be completely removed from the buildings sector by 2020 and hydrogenated chlorofluorocarbons (HCFCs) 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. Load control will also regulate the variable R-value wall panels and variable transmittance fenestration, to permit greater use of the external environment to improve internal comfort conditions and reduce energy use. 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 the use of porous pavement, turf paving, and grey water irrigation systems.

3.5 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 4.0 quads (11.2%) less energy use and 91 MtC (16%) 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 \$14 billion on efficiency improvements.
- In the residential sector, the greatest energy and carbon savings are achieved miscellaneous electricity, lighting, and water heating. In the commercial sector, the greatest energy and carbon savings are achieved in miscellaneous electricity, lighting, and space conditioning.

- 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 equipment are comparable to or longer than the analysis period (see Table C-2.8 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 of our Nation'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 onsite, 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.
- Climate-specific design 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 technology from improved controls, to more high-efficiency small sources matched to improved luminaires, to daylighting systems, to 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, 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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¹ Cost-effective technology in our analysis is defined generally as one 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 than the average cost of purchased fuel or electricity and hence cost-effective, we use a cost of conserved energy (CCE) calculation using the following equation:

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

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

³ Carbon emissions are derived from the product of end-use energy (by fuel) and carbon emissions factors of MtC/quad of primary energy taken from (U.S. DOE, 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. While miscellaneous energy (particularly electricity) can encompass a variety of activities, for the purposes of this study we have divided miscellaneous energy into three electricity categories: electronics (e.g. color televisions, video cassette recorders), motors (e.g. fans and pumps), and heating (e.g. waterbed heaters, coffee makers, crankcase heaters), and two non-electricity categories (natural gas, and oil & other petroleum products).

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 figure. For example, residential miscellaneous electricity carbon emissions in 2010 are 92 MtC but appear slightly greater (~94 MtC) in the Figure 3.2.

⁶ Major contributions to this section were made by George Courville, Mike MacDonald, Jeff Muhs, John Tomlinson, Jim VanCoevery, 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 (3) with long wavelength switching, the emissivity changes when the temperature of the radiative environment satisfies certain conditions.

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 technology which is commercially available, or near commercialization, into the market could make to reducing greenhouse gas emissions from the U.S. 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 limitations of the available analytical tools for this sector. We then describe the results of our model-based scenario analysis through the year 2010. In subsequent sections we provide examples of the types of technologies that, were they to come into widespread use in the U.S. industrial sector in the near term, would achieve the model scenario results. But widespread adoption of these technologies would require the appropriate policies (e.g., accelerated R&D, fiscal incentives and market conditions). Finally, we describe qualitatively, and illustrate with examples, the role of research and development (R&D) in providing a continuous stream of advanced technologies that can continue to reduce industrial energy intensity and greenhouse 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. 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, and 3) estimate the fraction of the plants that are not already using these technologies, and 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 that allow us 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, under an invigorated effort to move them into the market, would achieve the model results.

4.1.1.1 Scenario Analysis

For the scenario portion of the analysis, the preferred analytical tool would be an industrial model that is publicly-available, complete and up-to-date and that has a stock-adjustment mechanism and 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 U.S. Department of Energy's *Annual Energy Outlook 1997* (DOE 1997b), which is prepared by the Energy Information Administration using the National Energy Modeling System (NEMS).

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: 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 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 details on 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 case, and an High-Efficiency case. These cases are defined, and their results described, in Section 3.2. Our general approach was to use the Annual Energy Outlook (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 AEO¹. We then ran the adjusted LIEF model to obtain an Efficiency and an High Efficiency 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 High Efficiency case ("delta two"). We apply the LIEF model "deltas" to the NEMS (AEO 1997 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 those 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 thus achieve the savings that the models suggest are possible. While there are many reasons for the need for an invigorated effort to encourage the adoption of these technologies, some of which we discuss later, we have tried to temper our expectations and be sensitive to the generally slow turnover of heavy equipment in industry.² Another timing issue is that some energy-intensive industries also have "windows of opportunities" 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 model or are the focus of the DOE Office of Industrial Technologies' (OIT) Industries of the Future process, sometimes referred to as "Vision Industries": forest products³, 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.

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 additional energy intensity and greenhouse gas emissions reductions beyond those described in the efficiency and high efficiency 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 thinking 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. There must be continued R&D that is focused on efficiency improvements and carbon emissions reductions in order to generate the new technologies of the future.

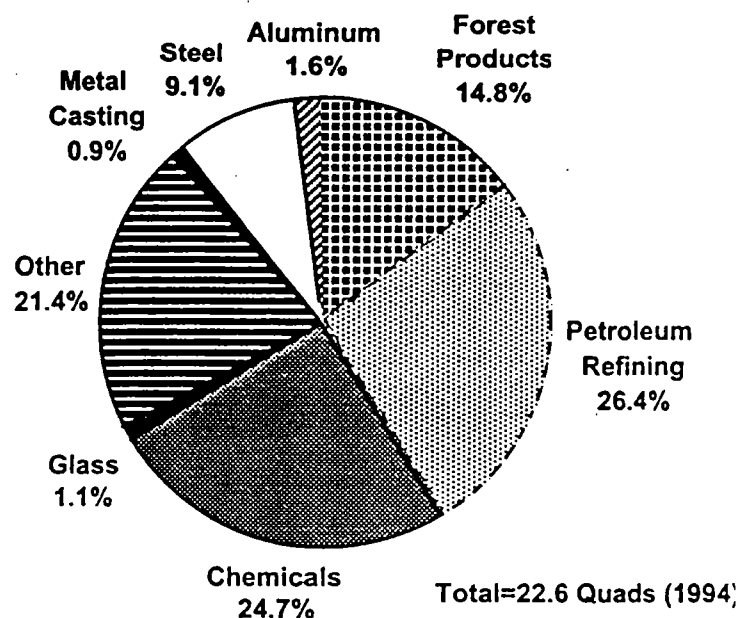


Figure 4.1: Share of Energy Intensive Industries in Manufacturing (End Use) Energy: 1994

4.2 ENERGY EFFICIENCY EMISSIONS REDUCTIONS

The Long-Term Industrial Energy Forecasting (LIEF) model is a compromise between a neoclassical, econometrically-estimated level of technology and a bottom-up engineering analysis. LIEF is an 18-sector model specifically used to study future industrial energy consumption. An important element of the LIEF model is that energy efficiency improvements and their costs are described by an equation that predicts the 'best practice' energy intensity, involving the level of expected energy prices and the capital recovery factor which serves as an implicit discount rate. This predicted level of savings, derived from comparing best practice and average practice energy intensity within a given industry, represents the available efficiency "gap". The model parameters, including the base year efficiency gap, has been estimated using time series data from the National Energy Accounts (NEA) for the period 1958 through 1985. Although the NEA data does not include the most recent movements in energy use and prices, the model developers believe that the parameters are still generally valid. The presence of an "efficiency gap" in LIEF implies that there are important opportunities to reduce energy use through 2010.

The LIEF model contains conservation supply curves for various industries that describe the extent to which industry is able to invest in energy conservation 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. 

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 superseded 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 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, 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 feedstock 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 used 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 to final consumers or to other manufacturing. In 1994, energy intensity was 16.0 TBtu/\$.

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. The *Minimills* 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/\$.

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 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 case. Further details on how the models were used to simulate these cases are provided in Appendix D-1.

4.2.1 Business as Usual Case

Our business as usual (BAU) case is the AEO97 reference case. Under this case, national economic output, measured by gross domestic product (GDP) is projected to increase by 2.1% 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 use intensity, to the year 2010, is projected to decline by 1.1% per year. Among industry sectors, the largest declines in total energy use intensity are projected for the pulp and paper and glass industries, with the cement industry third. Electricity use 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

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.

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% energy savings 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 is an appropriate BAU case for this study, since it 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 of industrial technology R&D performance, availability, and introduction, this means that current and future private and government R&D funding for new and emerging technologies that is consistent with recent history is, in part, responsible for 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. 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 efficiency 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 the former effect in LIEF by changing the Capital Recovery Factor (CRF) from 33% to 15% to reflect the lower hurdle rate. Since not all cost effective technologies are assumed to instantaneously penetrate the market, the High-Efficiency/Low Carbon 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. The results are shown in Table 4.1.

Table 4.1 LIEF Results: Change in Energy Intensity, Annual Average Rate, 1997-2010, Compared with the Business as Usual Case (percent change)

	Efficiency Case			HE/LC Case		
	CRF = 15%			CRF = 15%		
	Penetration = Normal			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%	-0.22%	-0.29%	-1.26%	-0.41%	-0.53%
All Industry	-0.64%	-0.30%	-0.43%	-1.28%	-0.60%	-0.85%

Table 4.1 shows the results of these analyses for 10 major economic sectors of U.S. industry. The results 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 0.4% per year. The High-Efficiency case reduces the growth in energy intensity by almost one percent per year (0.9%) additional, relative to the BAU case and reduces the growth in electricity use by more than one percent annually (1.3%).

Table 4.2 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 than 10% in 2010 relative to the BAU case, while the decrease in the Efficiency case is more than 5%. 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. This is because 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 seventies. Light industries' energy use is dominated by electricity, as well. 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. This 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, the majority of

the energy savings in absolute terms still come from fossil fuel use reduction in heavy industry, e.g. heavy manufacturing is about 8% while the industry total is about 10%.

Table 4.2 LIEF Results: Energy Savings , in the Year 2010, Compared with the Business as Usual Case (percent reduction)

	Efficiency Case			HE/LC Case		
	CRF = 15%			CRF = 15%		
	Penetration = Normal			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%	2.9%	3.7%	15.1%	5.2%	6.7%
All Industry	8.01%	3.9%	5.4%	15.30%	7.5%	10.4%

Table 4.3 translates the results reported in Table 4.2 into changes 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). The next two columns show the effects of the Efficiency case and the High-Efficiency case, as forecast by LIEF, on the AEO97 BAU case. Figure 4.2 shows that the High Efficiency/Low Carbon case approaches zero growth with energy use increasing by only 1 Quads (3%) between 1997 and 2010, in spite of an output increase of 30% over the period. The value of the energy savings represented by the HE/LC case in 2010 is \$5 billion for fossil fuels and \$9.1 billion for electricity (\$2.6 and \$4.8 billion for the Efficiency case).

Table 4.3: Total Industrial Energy Use: AEO97 Business as Usual Case and Forecasts by LIEF (Quads)

	AEO97		LIEF	
	1997	BAU 2010	Efficiency Case 2010	HE/LC Case 2010
Electricity (incl. related losses)	11.3	13.2	12.2 (8.0%)	11.2 (15.3%)
Fossil Fuels	21.4	24.2	23.3 (3.9%)	22.4 (7.5%)
Total	32.6	37.4	35.4 (5.4%)	33.6 (10.4%)

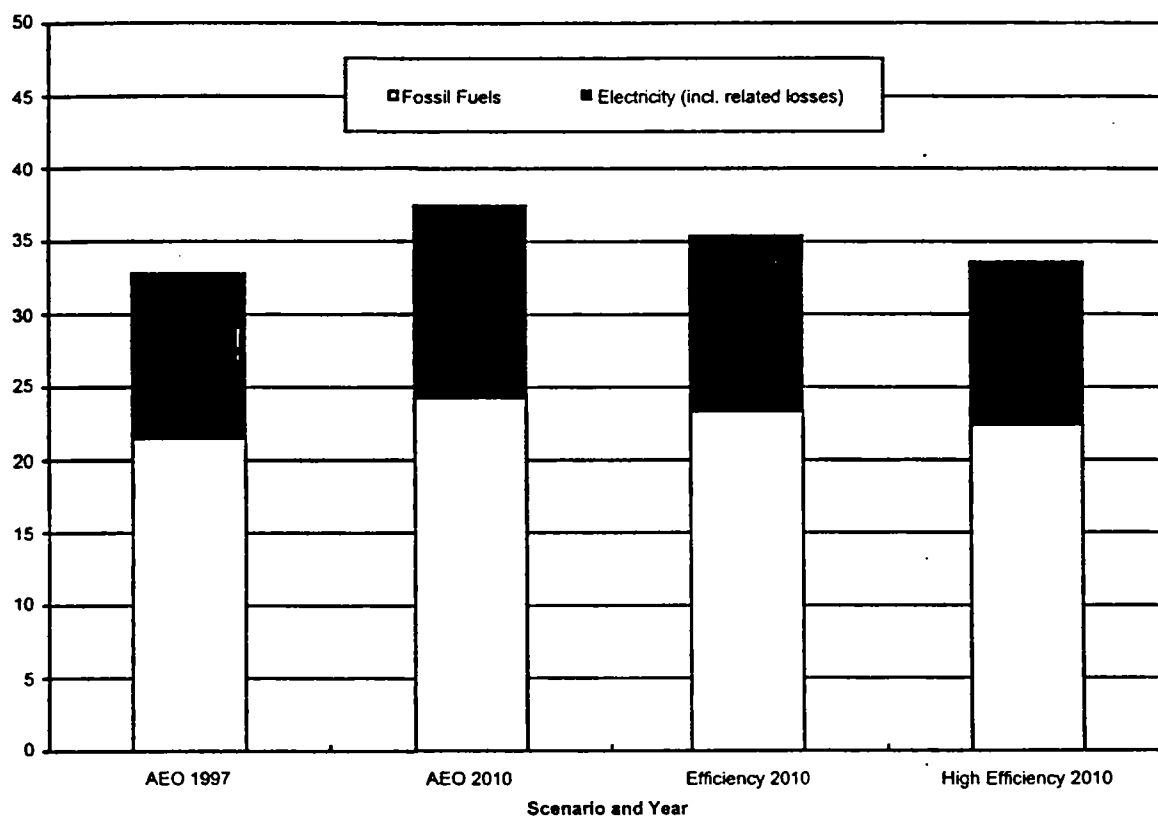
**Figure 4.2 BAU Energy Use and Projected Efficiency Cases in 2010**

Table 4.4 provides greenhouse gas emissions estimates for 2010 in metric tons. Because the LIEF does not model fossil fuel choice, the greenhouse gas emissions reductions estimates are based on the fossil fuel mix and emission factors in NEMS. For fossil fuels there are two ways to compute greenhouse gas emissions. The first is to assume that efficiency affects fuel reductions through the average fuel mix such that greenhouse gas emissions reductions are proportional to fossil fuel reductions. 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 4.4 Carbon Emissions Estimates - Million Metric Tons per Year
(Percent reduction in parenthesis)

	AEO97		Efficiency Case	HE/LC Case
	1997	2010	2010	2010
Electricity	172	201	192 (4.4%)	186 (7.4%) *
Fossil Fuels	311	334	321 (3.9%)	309 (7.5%)
Industry Total	482	534	512 (4.1%)	494 (7.5%)

*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/metric ton of carbon (see Chapter 6).

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%. Therefore, using the average industrial fossil fuel mix from the AEO97 is a reasonable approach to compute the change in greenhouse gas emissions. However, analysis of fuel mix in the electric utility industry shows that natural gas has a growing share, so that this approach would yield an upper bound estimate for carbon reduction arising from electricity savings. Therefore the carbon reductions for electricity use in Table 4.4 are based on the marginal carbon emission rates, rather than the average (see Chapter 6 for more details).

4.2.3 Comparison with the NEMS model

The NEMS model provides a different approach and perspective on the Efficiency and High-Efficiency cases. The NEMS model uses a stock turnover approach to project the change in energy use. New technology is projected to be more efficient, so 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 4.5). When the retirement rate of capital is doubled in the NEMS industrial model, total energy use declines between 1 and 8%, depending on the sector.

Table 4.5 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%

On the other hand, when the performance of new technology is assumed to double, i.e. new technology's relative energy intensity in NEMS declines twice as fast as the BAU case, even larger reductions in energy use are achieved for all sectors but 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 Efficiency and High-Efficiency case. In four out of six sectors (paper, Chemicals, Cement, and Iron and Steel) the NEMS runs provide a similar range of energy intensity reduction, compared to the efficiency and HE/LC cases. For aluminum and glass the double technology performance NEMS run generates higher energy savings, suggesting that for these sectors more rapid technology development is an important part of future savings. This is particularly true of the aluminum sector.

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. While much of the change occurs because of energy efficiency improvements over time, another substantial part of overall energy use changes occur because of 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 of the change. Put into historical perspective, forecasts of energy use and energy intensity changes used for this analysis are modest changes, and, we argue, 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. From 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 too do 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.⁵ Of the energy savings that occurred in the industrial sector between the mid 1970s and the early 1990s, this report (Figure 6, p. 8) suggests that about one-third of the total was attributable to compositional shifts (i.e., shifts from high energy-intensive industries to industry 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 (.6%) is attributable to projected composition effects. If one takes the efficiency component of 0.5% per year forecast of total intensity decline from the BAU case and adds the additional 0.85% per year from the High-Efficiency/Low Carbon case, the High-Efficiency/Low Carbon 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 4.6, 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 would be profitable given the forecast energy prices and a CRF of 15%, implying that the energy savings would provide about a 7-year payback on the initial investment. Since savings continue to accrue over the lifetime of the equipment, this is an investment with a profitable return. However, it is important to understand the magnitude of the up-front costs, since this may be an issue in designing policies to spur this enhanced technology penetration.

To put this level of investment in energy-efficiency into context the investment is compared to total investment in manufacturing. If the cumulative investment in energy efficiency is spread out evenly over the 13 year time period, the High-Efficiency case would require a \$3.6 billion total annual investment in fossil and electricity efficiency. 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 high efficiency case represents a 3.3% increase over the level of manufacturing investment for 1992.

Table 4.6 Cumulative Incremental Investment (1998-2010) for Energy Efficiency Implied by the LIEF Model to Achieve the Forecast Energy Reductions (Billion \$95)

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

Historical behavior 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.

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.

Table 4.7 shows the net cost (or benefit if the total cost is negative) of an up-front investment in efficiency in a *single year* – 2010, compared to the present value of the energy savings that would continue to accrue thereafter. The table is *not* a total investment / net benefit for the entire time period. 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. The fourth line is the present value (PV) of the cost savings, assuming our example of 15 year lifetime and 12.5% real discount rate. The final line is the benefit, i.e. the investment cost minus the PV of the reduction in cost. For the efficiency case, investments generate net savings of about one and a half times 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 4.7 : Net Costs of Private Investment for Energy Savings in the Efficiency and High Efficiency Cases (Costs are million \$1995)

	Efficiency		HE/LC	
	Fossil Fuels	Electric (End use)	Fossil Fuels	Electric (End use)
Investment	\$758	\$1,681	\$1,545	\$3,230
Annual Energy Change (TBtu)	-94	-47	-178	-82
Annual cost change	-\$301	-\$613	-\$571	-\$1,072
PV of cost change	-\$1,999	-\$4,063	-\$3,790	-\$7,109
Net cost	-\$1,241	-\$2,383	-\$2,244	-\$3,880

The high efficiency 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 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 means 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 and net costs. The NPV of energy savings from the HE/LC scenario in table 4.7 does not change, but the investment cost may be understated by the amount of loss due to any early retirement that may occur. Since the net cost (benefit) is still more than the total up-front investment we calculate, then unaccounted costs may be about twice our estimated energy efficiency investment, and still have the HE/LC scenario be viewed as 'cost effective' on average.

4.3 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 High-Efficiency case and could contribute to this projected decline. In addition, we provide examples of technologies that directly displace carbon.

For each energy-intensive industry, and for cross-cutting technologies, 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. We describe how each technology is used and what type of efficiency from which it draws its energy and cost savings.

Some technologies recover or reduce the production of waste heat in high-temperature applications; 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. Some examples are instructive. Continuous casting, widely adopted by the steel industry, is cost-effective based on its energy savings alone; but that is not the most compelling reason it has been adopted. Rather, 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 imply 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.
- 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 example are given below.

Many of these technology example exhibit energy savings of more than the 5-10%% relative to current average practice, but the turnover of the capital stock in the energy and capital intensive industries require our projections take this into account. In 13 years many of these technologies (and the 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. Therefore, these examples help establish the technical plausibility of the projections.

A number of opportunities exist in industry to reduce carbon or greenhouse gases (GHG) that have little to do with improvements in energy efficiency. Some of these require additions to the current technological mix; some require changes in codes and standards. Selective examples are provided in the sidebar on this page.

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.

4.3.1 Crosscutting Technologies

There are a variety of crosscutting technologies, i.e., those that are not process- or product-specific, in operation in industry. Some include the lighting and HVAC examples that are in common with 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. Cogeneration, sometimes referred to as combined heat and power (CHP), is the joint production of useful steam and electricity, either for on-site use or sales 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. Motor systems, in a similar vein, encompass a wide range of industrial applications are discussed here as an example of non-process specific efficiency applications.

4.3.1.1 Cogeneration

Thermal energy generated by the combustion of fossil fuels is used to generate both electricity and process steam. The advantage of such an approach is that little additional fuel is required

Industry Carbon Mitigation Strategies

Biomass Gasification. Food processing, wood products and pulp and paper are industries that generate large amounts of residual biomass. 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 Cogeneration, below) make this an economically attractive option.

Reduce Anode Events. When the anode used to provide current to an aluminum reduction pot comes in contact with the metal cathode, an anode event occurs that shorts out the cell and releases significant halocarbon emissions. Since these halocarbons have a much higher Global Warming Potential than carbon dioxide, reducing such events would decrease GHG emissions. Technologies such as wettable cathodes, inert anodes and improvements in cell controls could reduce anode events and also reduce CO₂ directly.

Slag Cement. Nearly all cement in this country is made from ground clinker intermixed with gypsum. For each ton of ground clinker, about half a ton of CO₂ is emitted as a result of the chemical reaction while another half ton is emitted from the kiln fuel. Both fly ash and slag from metal processing could be ground and mixed with clinker to make cement with somewhat different properties, but still a satisfactory building material. Most European countries currently allow such cements and have found that these cements last longer and are more tolerant to salt water than pure clinker cement.

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 green house gas emissions can be reduced by the application of cogeneration. Based on a typical boiler configuration, the gas turbine with heat recovery steam generation typically is the most cost effective. (Boyd, Molburg and Thimmapuram, 1996).

Critical to the efficiency of the cogeneration system is the efficiency of the turbines used to produce electricity. A new generation of advanced turbine systems (ATS) is likely to be commercially available soon after the year 2000. Estimates of a 22% lower CO₂ emission relative to the best available gas-fired-combined cycle central station electric generating system have been made for 15MW industrial ATS projected to be commercially available by the year 2000 (Major and Davidson 1997). The potential ability of ATS systems to burn biomass in turbine systems without fouling and maintenance problems is being explored via new turbine materials, like ceramics. If ATS can be economically fired with biomass, then substantial reductions in greenhouse gas emission will result. This will also require the evolution of a biomass fuel supply infrastructure or penetration will be limited to those industries, like forest products and some food processing sectors, that already have access to biomass fuels. An example of biomass based cogeneration in the paper industry is provided in section 4.3.2.

If the economic performance of ATS or other 'invigorated' policies make cogeneration more attractive in currently uneconomic regions and industries then kWh/Btu of boiler fuel use will increase. The ability of enhanced cogeneration penetration to displace electricity demand can be illustrated with a simple example. If those states or industries whose average cogeneration in kWh per btu of boiler fuel that is less than the US average, but more than 50%, increases to the US average then an additional 15 billion kWh would be cogenerated⁶. This amounts to a 9.5% increase in manufacturing cogeneration relative to 1994, or a 1.2% decrease in industrial electricity demand relative to 2010.

4.3.1.2 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. That 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%. Though 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 oversizing 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.

4.3.2 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 51%) 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 even higher – nearly 70%.

In paper manufacturing especially, any technology that will economize on 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:

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 could be approx. 0.25 quad/yr. Without an invigorated effort, the net energy savings have been estimated to be about 12 trillion Btu annually from a market penetration of only 65 drying units by 2020.

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 inside 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: While many people think of paper in terms of three grades, brown, white, and tissue, papermaking involves literally hundreds of grades. Current technology for some properties relies on spot samples individually tested in a paper-testing laboratory to determine whether the operation was on-grade at the time the sample was tested. 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 70+ billion Btu/yr. Reducing the normal off-grade production rate by 50% (from a typical 5% to 2.5%) can save an additional 118 billion Btu/yr. If 300 plants adopt these sensors, the savings would be about 60 trillion Btu.

4.3.3 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 liquify 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. 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. As with paper, the most 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 are commonly uses 30% to 50% more energy than necessary is used 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.

4.3.4 Petroleum Refining

The most energy intensive processes are: distillation; catalytic hydrocracking, reforming and hydrotreating; alkylation; and hydrogen production. Efficiency improvements can be achieved via 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.

4.3.4.1 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.

4.3.4.2 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)

4.3.4.3 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.

4.3.5 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.

4.3.5.1 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 (20 ton/day) furnaces 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).

4.3.5.2 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.

4.3.5.3 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).

4.3.6 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 (BOM 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 timeframe to 2010.

4.3.6.1 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 10 years (Energetics 1997). The primary barriers to adoption of high efficiency technologies may be economic, however.

4.3.6.2 Materials Recycling

Remelting aluminum scrap requires only a small fraction of the energy required to smelt aluminum from alumina. In 1995, aluminum recovered from old scrap was equivalent to about 34.4% 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.

4.3.6.3 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 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).

4.3.7 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 somewhat limited by scrap quality issues.

4.3.7.1 Direct Smelting / Direct Reduction

The ongoing process development activities in ironmaking 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 steelmaking operations and the material can be cooled to iron shot or ingots without reoxidation.

4.3.7.2 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 <300 kWh/tonne 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% are estimated and reduced electrode consumption of 29%. 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.

4.3.7.3 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 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).

4.3.8 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.

4.3.8.1 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. 1996) which would comparably reduce energy use for metal remelting.

4.3.8.2 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 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).

4.4 EMISSION REDUCTIONS FROM LOW CARBON TECHNOLOGIES

4.4.1 Introduction and Summary

"Low Carbon" technologies are technologies that reduce greenhouse gases through means other than energy efficiency. "Low Carbon" technologies can be divided into two types. The first type, "Fuel-switching" technologies, reduce carbon emissions in power and industrial applications by using low or no-carbon fuels instead of high carbon fuels. Because they are focused on energy, they are often grouped with energy efficiency technologies. The second type, "low-process-carbon" technologies, reduce or avoid the emission of carbon dioxide and other greenhouse gases in industrial and other processes. Most of these emissions are non-CO₂ greenhouse gases that are created from industrial processes or as by-products, and are not linked directly with combustion. Because these emissions do not involve energy, they are often ignored in energy-focused carbon analyses. However these emissions comprise nearly half of current carbon equivalent emissions in the industrial sector.

In the following sections we provide examples of these two types of low carbon industrial technologies. Section A: describes two fuel switching technologies. The first technology replaces coal fired industrial boilers with natural gas fired efficient turbines. The second technology replaces biomass boilers and grid electricity with biomass gasification cogeneration biomass fueled boilers. Section B: describes two "low process carbon" technologies. The first example, the advanced aluminum production cell shows that for some industrial processes, there are multiple opportunities for reducing carbon emissions. In addition to reducing carbon through improved energy efficiency, this technology eliminates carbon dioxide emissions associated with the carbon anode, and it eliminates PFC emissions (a potent greenhouse gas) associated with cell instability. The second example involves the substitution of waste products (flash and blast furnace slag) for a portion of the calcined cement clinker intermediate product.

A summary of the carbon reductions from these technologies is given in Table 4.4.1 for both the high efficiency and the high efficiency/low carbon cases. As in the previous discussions, a range is shown for the high efficiency/low carbon case. A more detailed description of these examples is given in the following sections.

Table 4.4.1: Examples of Low Carbon Technology Carbon Reductions by 2010 (MMTCe)

Carbon Reductions (MMTCe) of Low Carbon Industrial Technologies in 2010		High Efficiency Case	High Efficiency/Low Carbon Case
Fuel Switching Technologies	Advanced Turbine System	2-4	9-17
	Forest Products--Black Liquor	-	2-5
	Forest Products--Hogged Fuel	-	2-5
Low Process Carbon Technologies	New Al production cell	2-3	3-4
	Cement Clinker replacement	-	1-2
Total		4-7	17-33

4.4.2 Fuel Switching Technologies

4.4.2.1 Advanced Turbine Systems (ATS)

Potential: One of the major carbon-reducing technologies for the industrial sector between now and 2010 is a high efficiency, environmentally superior, natural gas-fired turbine that "cogenerates" electricity and steam. The Advanced Turbine Systems program is developing these next generation gas turbines for industry and electrical generation. These turbines, when introduced in 2001 (assuming that if the ATS program is funded on schedule), will have CO₂ emissions 21-61% lower than conventional technology. (Major and Davidson 1997) Covering the 3 to 18 MW size as a single unit (9 to 80 MW in multiple units), these machines are 43% efficient in simple cycle and can be 80% efficient when used for cogeneration. There have been several recent assessments of the potential of ATS to reduce carbon in the industrial sector. Based on these and our own analysis. Our estimate is that by 2010, 10-15 million additional metric tons of carbon equivalent (MMTCe) of industrial carbon emissions will be avoided due to the ATS in the efficiency case and 15-25 MMTCe will be avoided in the low carbon/high efficiency case.

Energetics, Inc. One analysis conducted for DOE/OIT uses a top-down approach that relies upon the cogeneration and non-utility predictions of the Annual Energy Outlook (AEO97) reference case (developed using the NEMS model). The AEO97 cogeneration estimates are based on the assumption that the historical relationship between industrial steam demand and cogeneration will continue in the future. The data source for this historical data, EIA's Annual Nonutility Power Producer Report, consists of data from approximately 400 cogenerators for 1989- 1994.

Energetics assumed that the industrial ATS would provide significant carbon savings over the AEO baseline in both the cogeneration and the non-utility market. Industry portion of these market is calculated based on 1991 industry cogenerated electricity data (MECS, Dec. 1994) as a percentage of the total electricity cogenerated in AEO 96 (AEO, Jan. 1996). Industry's share of the total generated electricity is based on historical ELA data¹. There will also be ATS penetration in other markets, but the ATS carbon savings in these markets is assumed to be similar to the baseline. The overall the technical potential capacity for industrial generation in these markets is 49 GW. This is the net potential electricity generating capacity based on projected replacements with ATS systems. ATS is assumed to capture 10% of the new capacity and 1/3 of the replacement capacity for a total potential of 28 GW. Table 1 shows the GW potential for new (nc) and replacement (repl) capacity in these markets.

In order to calculate the carbon reductions due to ATS, these markets are further subdivided into displacement of coal steam or gas-fired combustion turbines. Carbon dioxide reductions were calculated by multiplying the difference of the emission factors (coal steam vs. ATS and combustion vs. ATS) by the projected generating capacity and estimated service load (6500 hours). (Carbon Equivalent reduction (CE) is calculated from carbon dioxide reductions using the ratio of molecular weights of CO₂ and carbon ($44/12 = 0.27$)). Replacements in the non-utility market is the largest capacity and carbon category accounting for 2.8 of the total 8.9 MMTc savings. Carbon reductions due to displacement of boiler emissions were not considered. This analysis explicitly excluded bio-mass power (mostly hog fuel and black liquor boilers in the forest products industry) because they are considered elsewhere.

Table 4.4.2. Potential Capacity and Carbon Analysis Based on Energetics Analysis

Market		Industrial Capacity(GW)	Carbon Reductions (MMTc)
nc-cogen	coal-steam	15.5	0.8
	combustion turbine		3.1
nc-non-utility	coal-steam	2.3	0.3
	combustion turbine		0.6
repl-cogen	coal-steam	3.6	0.7
	combustion turbine		0.6
repl-non-utility	coal-steam	6.9	1.3
	combustion turbine		1.5
Total		28.2	8.9

Onsite Analysis: Another analysis conducted for ORNL by Onsite Energy Inc., (Major and Davidson 1997) is a bottom-up analysis that begins with the steam draw capacity that is currently provided by boilers. It did not consider the cogeneration replacement market. This steam boiler capacity estimate was drawn from MIPD database (Major Industrial Plant Database, Petroleum Information Corporation). The MIPD database consists of 20,000 U.S. industrial plants and accounts for approximately 90% of all industrial energy use. Onsite then calculated the equivalent electric generating capacity for these boilers from the electric/thermal (E/T) ratios. For those boilers that would produce electricity in the industrial ATS range (1-40MW), Online then estimated the fraction that could use ATS for this purpose. Based on a

¹ Nonutility - 73% based on EIA, "Annual Nonutility Power Producer Report", Vol. 2, 1994. Cogenerated Power - 50% based on MECS (1994) and AEO (1996). (Energetics used AEO96 in place of AEO97 because AEO97 did not breakout utility and nonutility generated power)

detailed analysis of the chemicals and the food industries (Major 1997), Onsite estimates that half of this boiler capacity could be technically replaced by an ATS. From this, Onsite estimated that the potential technical potential capacity for industrial ATS cogen in 2010 is 90 GW (see Figure 1). Based on the market projection of Solar Turbines and assuming that Solar captures 1/3 of the ATS market, Onsite estimates that by 2010, the ATS turbines will be responsible for 35GW of (Carroll 1997 and Major 1997) industrial electric co-generation. Onsite then calculated the displaced emissions of industrial boilers and the 2010 electricity grid as shown in Table 4.4.3. Based on the difference between the baseline and arrived at an additional carbon savings due to industrial ATS of 27 MMTCe. Since this does include the forest products boilers, about 10 MMTCe (the 2010 carbon reductions due to replacement of hog fuel and black liquor boilers) should be subtracted to make this more comparable with the Onsite analysis.

Table 4.4.3: Onsite Carbon Analysis

2010 carbon comparison	2010 baseline emissions MMTCe (%)	2010 ATS
Boiler Offset	8.2 (15)	27
T&D	3.2 (5)	
Oil	1.8 (3)	
Gas	5.6 (10)	
Coal	36.2 (67)	

Integrated Analysis: These two studies are examining similar markets--industrial self generation. It is quite that there is substantial overlap between the Onsite steam draw replacement market and the Energetics cogeneration and non-utility markets. However, the vastly different methodologies preclude quantitative comparison. As shown in Table 4.4.4, both the Onsite and the Energetics analysis appear to over- or underestimate important factors.

Table 4.4.4 Comparison of Two Analyses

	Cogen replacement	New cogen mkt	emissions reductions due to boiler replacements	new non-cogen (=non utility)
Onsite	- not considered	+ 90 GW technical potential >> economic potential since economics (e.g. of retiring boilers, of profiting from selling excess power, capital) not considered	+assumed for all cases	-/+ not considered (but probably part of new cogen)
Energetics	OK-ATS gets 1/3	+/- technical potential is underestimated because electricity-selling cogen is not considered. Economic potential is overestimated since ATS is assumed to get all new capacity.	- not considered	+assumes that ATS captures all new capacity.

Based on this comparison, we have chosen to use the Energetics approach, supplemented with additional assumptions derived from the Onsite analysis. The reason for this choice is the reproducibility of the market penetration. The only "economic analysis" in the Onsite analysis is result used in the Onsite analysis is Solar Turbines' estimate that it will capture 12 GW by 2010. Presumably this proprietary Solar analysis contains some of the same factors considered by the AEO analysis, but this cannot be checked². Going across Table 4.4.4, in the first column, we have accepted the Energetics analysis of the replacement cogeneration market. For the disagreement in the second column, we come out somewhere in-between at ___ GW of capacity. Energetics technical potential assumes no cogenerators sell power, while Onsite's assumes that they all do. Thus the technical potential is taken to be ___ GW (somewhere in-between 49 and 90). For the economic potential for new capacity, Onsite's estimate of 35/90 GW of new capacity seems more reasonable than Energetics assumption of 100% in new markets. Thus we have an economic potential of ___. For the third column, we again use an Onsite scaling factor with the Energetics bse. If we add to the Energetics analysis the carbon emission reductions due to replacement of boilers, there is an additional 1.3 MMTcE of savings. Finally if we assume that a fraction of the non-utility new capacity and replacement is a cogeneration ATS rather than simple cycle, we obtain another (___)MMTcE of emissions reductions. The low carbon scenario increases the fraction of cogeneration to ___ resulting in ___ MMTcE of savings.

Background: The ATS's remarkably high energy efficiency and low emissions stem from multiple incremental improvements applied in a novel manner. One of these innovations is the ATS "recuperator" that recycles waste heat to produce steam. The use of this cogenerated steam displaces industrial boilers and associated emissions. Many other innovations, including single crystal and directionally solidified turbine blades, combustor liners, nozzle alloys, and thermal barrier coatings together dramatically improve the ATS energy efficiency by gaining temperature and reducing the need for cooling. (Wilken 1996) The next generation of industrial turbine engines will have a thermal efficiency that is 15 percent greater than current systems and electricity costs that are 10 percent lower. The availability of these turbines will double the rate of new co-generation capacity and save almost three quads of energy nationwide annually by 2020. The major manufacturers in the U.S. are all projecting that their sales will double or triple by 2010 and ATS will have captured 15 percent of U.S. power generating capacity (Major 1997). By 2005, these turbines could have a \$6 billion per year global market. The U.S. Department of Energy is partnering with two major gas turbine consortiums. One, lead by Solar Turbines, is developing a recuperated, low pressure ratio (9:1) engine in the 5 MW -15 MW range. Allison is developing an aeroderivative engine with high pressure ratio (30:1) in the 13-18 MW size range. Both systems are optimized for dual firing with natural gas and oil but can handle a variety of other fuels. (Parks, 1997)

Costs: Equipment costs are in the 350-450\$/kW range. It is anticipated that the system would be competitive against 35\$/Mwh electricity purchases or \$3 per MMBtu. (Brent 1996 and Major 1997) See Figure 4.

Environmental Sustainability: The turbines have low emission combustion systems generating <9ppm NOx through lean premix combustion and < 5 with catalytic combustion with no other major pollutants. When deployed in 2001, ATS systems, per MW, will produce lower levels of

² AEO97 states that non-utility generators have a highly leveraged capital structure compared to that of investor-owned regulated utilities. AEO97 assumes that the financial structure of nonutilities is 80 percent debt and 20 percent equity. It also assumes that the cost of equity for nonutilities is 1.5 percentage points higher than that for utilities, while the cost of debt to nonutilities is 0.75 percentage points higher.

CO₂ and NO_x (77-95% less) than competing power generation technologies. (Major and Davidson 1997).

4.4.2.2 Offsetting Utility Generation Carbon Dioxide Emissions in the Pulp and Paper Industry - a high carbon to no carbon option (By Ralph P. Overend and H. L. Chum, NREL)

Integrated gasification combined cycle technologies (IGCC) can impact the pulp and paper industry significantly in two ways – by increasing the energy self generation and by utilizing better the forest management and process residues while improving the energy and environmental performance of the industry. High carbon potential offsets range in the 10 Mtc/y by 2010 at aggressive market penetration. Business as usual would only achieve half of these offsets. To achieve the aggressive market penetration possible it will be necessary to facilitate the commercialization of the first few units so that the industry learns by doing how to reach a fully competitive investment with those of conventional boilers for a much more energy and resource efficient technology.

Background: The pulp and paper industry purchases 43% of its energy from a variety of sources 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%. We show this complex purchased fossil fuel and energy pattern in Figure 4.4 (Miller Freeman, 1984-85; and each year from 1986-1997).

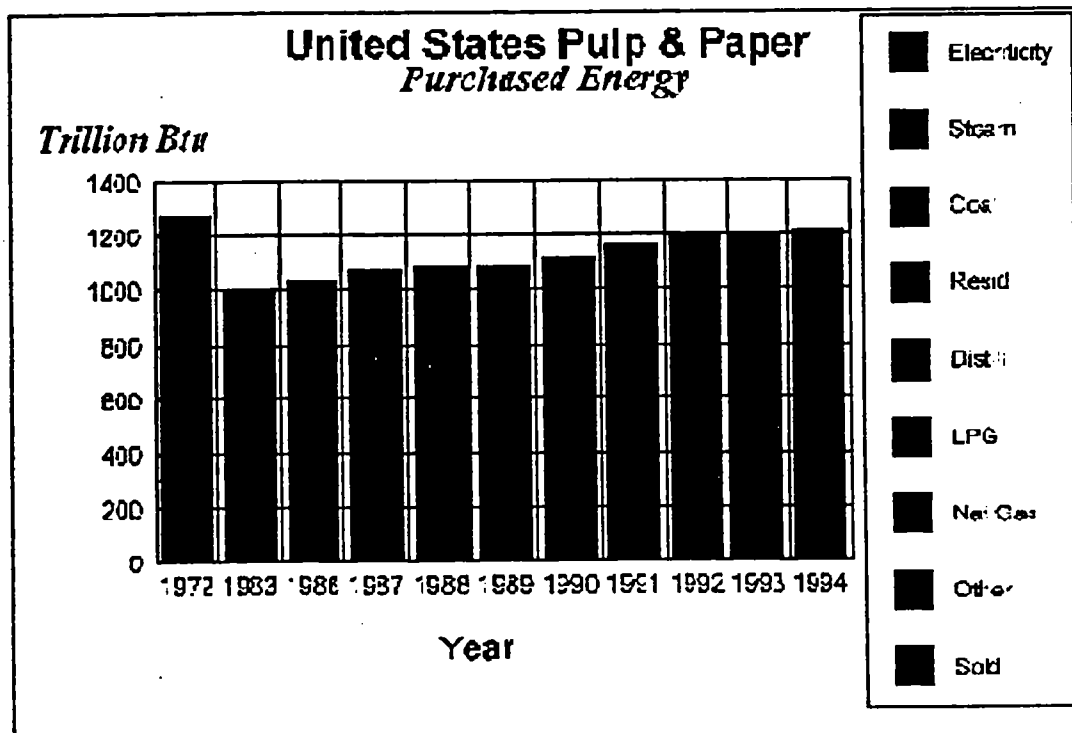


Figure 4.4: Purchased Energy in the Pulp and Paper Industry by Fuel Type Over the Past 22 Years

The industry generates 57% of its energy needs through the recovery of energy and chemicals in its spent liquors from wood chemical pulping through the kraft process, use of its residues such as hog fuel and bark in boilers, and cogeneration of heat and power (see Figure 4.5). The American Forest and Paper Association (AF&PA) estimates that renewable fuels use displaced more than 227 million of barrels of oil in 1994 (Miller Freeman, 1996).

These fuel switches, increased cogeneration, and energy conservation in the industry meant that in 1994 production of a ton of paper and paperboard used 21% less energy than in 1972 (Miller Freeman, 1997). Energy consumption per unit of product output decreased but electricity consumption increased.

We analyzed two opportunities in detail: increase self generation from black liquor and increase fossil fuel independence by extracting increased amounts of usable energy from hog fuels and bark coupled with increased recovery of forest residues and pre-commercial thinnings. Increased generation offsets purchases of electricity and coal and thus emissions of carbon dioxide³. These higher efficiency processes also increase industry's electricity production.

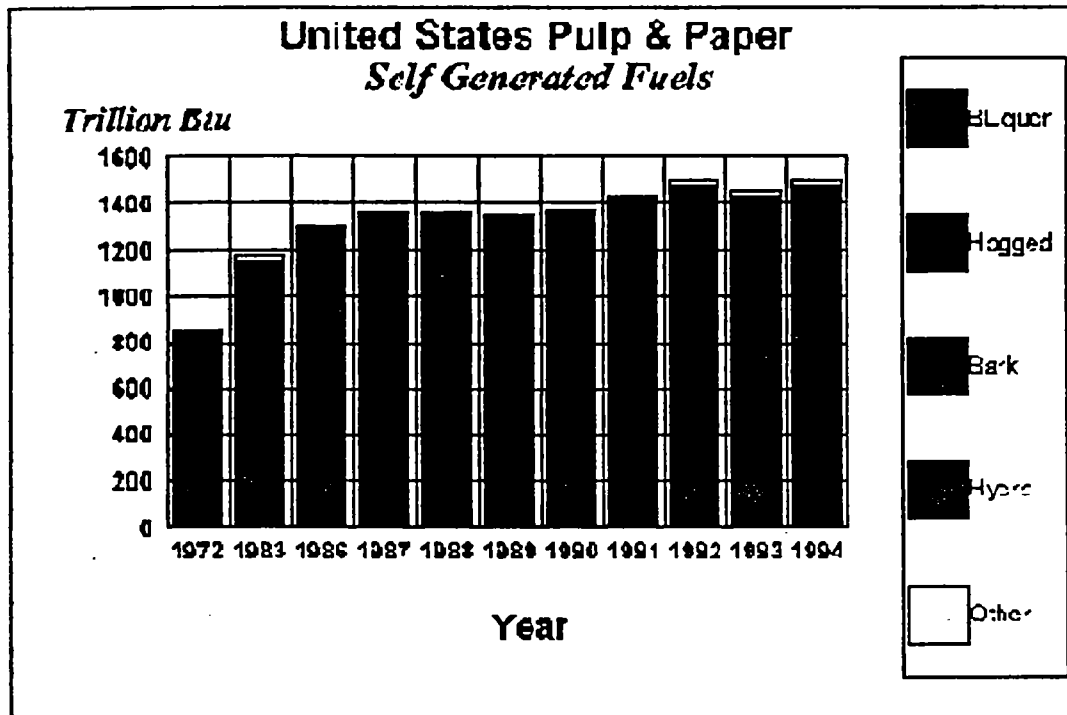


Figure 4.5: Self Generated Fuels in the Pulp and Paper Industry by Type in the Past 22 Years

4.4.2.2. Hog and Bark Boiler Replacements

Potential: By using wood and fiber residues from pulping processes as well as additional biomass from forestry operations, in conjunction with gasification and combined cycle

³ The calculations performed for both cases were reviewed by the American Forest and Paper Association and industry representatives (David Cooper and Delmar R. Raymond).

technologies, an additional 2.3 GW of capacity can be put in place by 2010, offsetting 4.8 million tons of carbon per year. This would represent about 1/3 of the potential mill conversions projected to need replacement by that time.

Background: Approximately 200 mills are already producing heat and some power from the use of residues such as bark and wood (hog fuel) in their processes. The current electricity production is mostly for within mill use. The majority of the boiler units entered into service in the decade between 1965 and 1975 and need replacement as they reach their service lives and may have difficulty meeting current environmental regulations. IGCC has an opportunity to penetrate the replacement market with the potential to double the net rate of electricity generation from these resources (from a generation efficiency of about 15% to a level of 35%). These technologies are already in the early stages of full commercialization with the first 18 MW output IGCC operating in Sweden and prototype units being demonstrated elsewhere in Scandinavia and the USA.

The residue generation is specific to the feedstock composition to the kraft mill or other conversion. For kraft pulp the relative species mix for the USA was 72.8% softwood, and 27.2 % hardwood (USDA, 1990). The assumed average conversion rate is 2.8 dry tonnes per one tonne of kraft pulp (the 1990 value). Data from the SE shows that saw timber (larger diameter - bark and slabs as residues) result in softwood and hardwood residue generation rates of 0.062 and 0.22 tonne/tonne of kraft pulp respectively. Pole timber in contrast has a lesser diameter criterion and results in 0.007 t/t and 0.068 t/t for softwood/hardwood respectively. Additional residues come from stand conversion activities (salvageable dead trees, cull trees, and trees less than 12.5 cm diameter), and have a much higher ratios of 2.25/3.63 t/t, softwood/hardwood to pulp product. Stand conversion activities are region specific (Larson, 1991).

Additional biomass collection from the mill forestry operations in the form of pre-commercial thinnings, harvest residues, and residue acquisition from sawmill and other operations in the same region could increase the fuel available by 100% which would allow a typical 750 tons per day pulp mill to produce 35 MW for export to the grid to offset utility generation (Weyerhaeuser, Stone and Webster, Amoco, and Carolina Power and Light, 1995). For the New Bern, N.C. region this study developed a supply curve shown in Figure 4.8. The technology for increased recovery of residues and pre-commercial thinnings in plantation forestry is developed and there is experience in its deployment. The developed calculations remained at the first third of the supply where the feedstock can be obtained at under \$21/BDt.

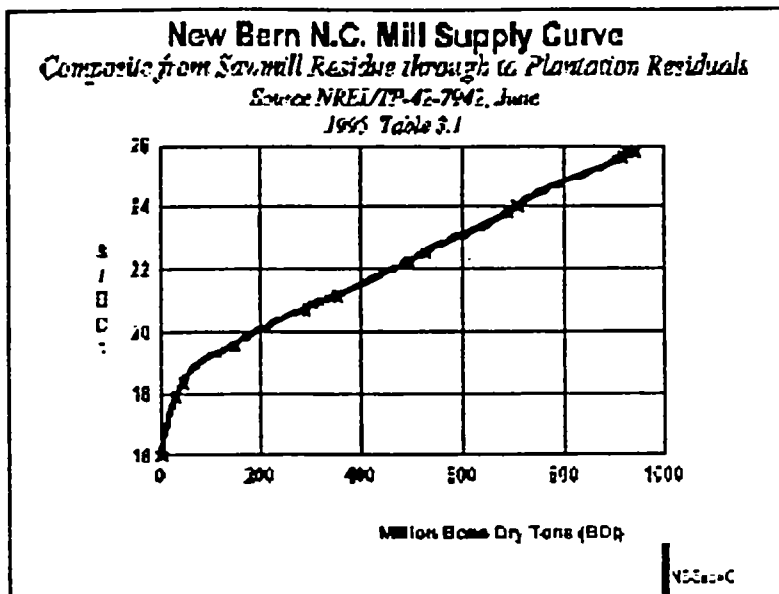


Figure 4.8: Example of Biomass Shed Developed for a Specific Weyerhaeuser Mill (New Bern, NC)

Costs: In the example of the New Bern mill, although more complex, the effective first generation plant based on a Frame 6B gas turbine and current gasification systems compared well with a stand alone plant at 1750 \$/kW total plant investment and an overall efficiency of 30%.

Barriers and their removal: The current cost of IGCC is approximately 50% over the Nth plant cost. A proposal is for the industry to form a "buyers's club" that orders 5 or 6 units with government capital cost buy down to create the Nth unit rapidly without any one customer being penalized by either cost or operational difficulties as the learning curve is followed. A sum of 300 M\$ has been proposed - a 50% buy down on 6 units with a total combined electricity production of 420 MW (with an electricity export of 50%, retaining 50% for self use). This cost is predicated on the \$100 million of capital cost for the unit assumed at 750 tons per day.

Environmental Sustainability: The IGCC system is designed to meet NSPS and would have low NO_x and SO_x. Biomass growth and harvesting would be according to best practices - and to some extent the fuel sources could include materials that currently go to landfill and might produce methane.

Carbon Replacement: Offsetting 4.8 Mtce/y is possible using 1/3 of the potential mill conversions that are projected to need replacement at that time. Because of the stage of development of the technology and its markets, a conservative estimate would only reduce from 1/3 to _ the potential mill conversions. With the more conservative penetration, the carbon replacement potential decreases to 3.6 Mtce/y.

4.4.3 Low Process Carbon Technologies

4.4.3.1. Process Carbon Dioxide Emissions

Overall, the industrial sector directly emitted about 23 million metric tons carbon from carbon dioxide industrial processes. There has also been a disproportionate increase in process carbon dioxide emissions. Sources of process carbon dioxide emissions vary dramatically by industry sector (See Table 4.4.5).

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 iron smelting, steel making, glass manufacture, flue gas desulfurization);
- dolomite consumption;
- soda ash manufacture and consumption (e.g., in glass manufacture, flue gas desulfurization, and chemicals production);
- carbon dioxide manufacture;
- gas flaring and
- aluminum production.

Table 4.4.5 Process Carbon Emissions and Energy Use by Sector

Industry ^a	Carbon Emissions (MMTCe)			Energy Use (Quads)
	Process Carbon Dioxide ^c	Other GHG Carbon Eq.	Total Carbon	
Manufacturing	18.4	32	50.4	22.4
Service	0	59.2	59.2	
Agriculture	0	66.7	66.7	
Mining/ Energy Extraction	0.9 ^f	61.5	62.4	
Construction	2	0	2	
Total Industry	21.3	219.4	240.8	32.6
Buildings	0	5.3	5.3	33.7
Transportation	0	19	19	25.5
Total	21.3	243.8	265.1	91.8

c—from the report "Emissions of Greenhouse Gases in the United States 1995, October 1996 DOE/EIA -0573(95)

f- Gas Flaring

Over the past eight years these emissions have increased nearly 16 percent while combustion-related carbon dioxide emissions have increased only 4%. This increase has not been steady and the data have varied considerably. These process carbon data are highly uncertain due to the variability and in current techniques for measurement. For example, they may be consistent with flat carbon intensity.

4.4.3.2 Industrial Sources of non-CO2 GHGs

Although industrial emissions of halocarbon are small by weight, they have global warming potentials (GWP) that range from 21 for methane to 23,900 for sulfur hexafluoride.

The following industries emit significant amounts of (non-CO₂) greenhouse gases, as well as CO₂: Chemicals, Aluminum, Manufactured products for the electric utility industry, Semiconductor Manufacturing, Metal Casting, Steel

CHEMICALS:

- 0.4 MMTCE of methane
- 9.1 MMTCE of Nitrous Oxide
- 1.3 MMTCE of process CO₂

Methane emissions from chemical production reflect general trends in the economy. Emissions grew at an annual growth rate of more than 8% from 57,000 metric tons in 1991 to 72,000 metric tons in 1994. A significant portion of this growth can be attributed to an increase in emissions from production of ethylene and styrene. Production of ethylene grew by more than 20% during the 1991-1994 time period, and production of styrene grew by nearly 40%.

Nitrous Oxide is emitted as a by-product of certain chemical processes. Principle sources include adipic acid and nitric acid. Emissions from these two processes have increased by 9.9% since 1990, although they remained stable from 1994 to 1995. Adipic acid is used to manufacture nylon fibers and plastics including carpet yarn, clothing, and tire cord. Other uses include production of plasticizers for polyvinyl chloride and polyurethane resins, lubricants, insecticides and dyes. With current technology, for every metric ton of adipic acid produced, 0.3 metric ton of nitrous oxide is created.

Nitric acid is a primary ingredient in fertilizers. It is produced by oxidizing ammonia with a platinum catalyst. One study shows that N₂O is produced at a rate of 2 to 9 grams of N₂O per kilogram of nitric acid manufactured.

ALUMINUM:

(see aluminum case study) Almost all Perfluorocarbons (PFCs) are emitted by the Aluminum industry. A very small amount is emitted by the semiconductor industry.

MANUFACTURING components for the electric utility industry:

- transformers
- circuit breakers / load-shedding devices
- electrical distribution

Manufacturing these components causes emissions of Sulfur Hexafluoride amounting to 4.4 MMTCE. Sulfur Hexafluoride 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. Global emissions are increasing at a rate of 7-8% per year. Total Emissions in the U.S. in 1994 were 1.135 thousand short tons, on a molecular basis. (US EPA National Air Pollutant Emission Trends, 1900-1994; Table 10-4) This is equivalent to 6.7 MMTCE. It is important to note that while U.S. emissions were about 1000 metric tons in 1994, domestic sales were six times greater at about 6,000 metric tons. This means that the "banked" inventory of SF₆ is growing quickly.

Perhaps as much as 60-70% of world production of SF₆ is used by the electric power industry worldwide. The U.S. utilization of SF₆ is likely to be similar to the world profile. If 60-70% of SF₆ emissions are used in the electric power industry, this amounts to 4-5 MMTCE in the U.S.

Of all of the uses in the electric power industry, switch gear seems to be the most critical, because substitutes are not readily apparent. Several DOE technologies may be immediately helpful.

For bulk power switching, a solid state switch has been jointly developed by the DOE and DoD (Navy), possibly for nuclear subs and aircraft carriers. A solid-state switch for bulk power would not require SF₆. For transformers, near-term applications of DOE's high temperature superconductor research include transformers and current limiters that act as circuit breakers.

METAL CASTING: -1.2 MMTCE of SF₆

MAGNESIUM CASTING:

SF₆ is used as a "cover gas" over the molten magnesium surface to protect against "catastrophic oxidation." Small amounts of the gas are pumped into the furnace plenum with other gases like CO₂. SF₆ is used in trace amounts ranging from 0.03 to 4% of the total cover gas. Surface chemistry at the cover gas / molten metal interface is poorly understood.

Less than 10% of world production of SF₆ is used for magnesium casting. Most likely estimates are 6-7%. If the U.S. consumption is similar to world consumption, emissions of SF₆ amount to 0.4 - 0.5 MMTCE. Currently, primary smelters are looking to find a substitute gas.

SEMICONDUCTOR PRODUCTION:

Six gases with high GWP are used during production of semiconductors. These non-carbon gases include: SF₆, CF₄, C₂F₆, C₃F₈, NF₃, CHF₃.

Primary uses of these gases include:

- plasma etching
- Chemical Vapor Deposition
- CVD chamber cleaning

In total, use by the semiconductor industry of all 6 gases is about 1 MMTCE per year. Of this, SF₆ represents about 0.1 MMTCE.

STEEL:

- 0.3 MMTCE methane
- 0.7 process CO₂

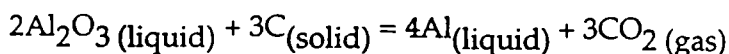
Methane emissions from iron and steel production are linked to rates of economic activity. Emissions from iron and steel production reached a peak of 64,000 metric tons in 1989, declined to 54,000 metric tons during a 1991 recession and reached 61,000 metric tons in 1995.

4.4.3.3 Low-Carbon Technologies in Primary Aluminum Production

Potential: By 2010, nearly a quarter of the carbon emissions associated with primary aluminum production could be eliminated through aggressive R&D and commercialization of an advanced aluminum production cell. The advanced cell would eliminate cell instabilities that cause halocarbon (CF_4 and C_2F_6) emissions by 2010. Under the "efficiency" scenario, the "wetable" cathode part of the cell, which accounts for at least 80% of the carbon savings, could achieve significant market penetration by 2010. Under a "high-efficiency/low-carbon" scenario, carbon anodes, could also be eliminated, eliminating carbon dioxide (CO_2) emissions associated with consumption and manufacture of these anodes. Under this scenario, R&D on this advanced cell would be aggressively funded by both the federal government and the private sector. Research and commercial-scale tests (a full plant demonstration, including the actual conversion of a potline) would be completed in time for significant market penetration of the cell in 2010. (Kenchington).

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 its commitment to eliminating process CO_2 emissions in primary aluminum by the year 2010 (Energetics). Furthermore, trends toward increased use of aluminum in the transportation sector to improve vehicle fuel efficiency through weight reduction could significantly increase U.S. demand for primary aluminum, potentially stimulating the economic feasibility of the advanced cell technology. If 50% of retrofitable capacity (8 or 9 of 22 plants) (EPA) used the advanced cell by 2010, carbon emissions would be reduced by 2 to 4 MMTc compared with the baseline (assuming 1990 production).

Background: All primary aluminum is produced by the Hall-Heroult process, which has evolved and improved continuously since it was first commercialized in the early 1890s. In this process, aluminum oxide (alumina, or Al_2O_3) dissolved in a molten cryolite solvent is decomposed into molten aluminum (Al) at a negatively charged pool of aluminum (the cathode) and oxygen at a positively charged carbon anode. The oxygen reacts with the carbon anode to form CO_2 , as shown below (Haupin):



The carbon anode is consumed in the process and must be replaced every 2 to 3 weeks (Emad). A direct short in the cell will occur if the anode comes into contact with the molten metal. Maintaining the correct anode-cathode distance to avoid the short is difficult because the anode is consumed unevenly and the surface of the molten aluminum undulates. In practice, therefore, the anode and the cathode are kept at a distance of at least 4 centimeters apart. The inter-electrode distance is proportional to the voltage requirements of the cell and thus the cell's thermal efficiency. Currently, heat losses resulting from the extra inter-electrode distance account for approximately 40% of the energy consumption of a typical cell (Evans).

The anode-cathode distance could be reduced up to 50% in an advanced cell incorporating the following (Kenchington) advanced cell features:

- "inert" anodes to replace consumable carbon anodes, thereby eliminating uneven anode surfaces
- solid "wetable" cathode surfaces to replace the molten aluminum cathode, eliminating undulating cathode surfaces

In addition to reducing cell electricity requirements (and reducing the CO₂ associated with generation of this electricity), the use of inert anodes will eliminate the process CO₂ emissions from smelting (those associated with anode consumption). The use of inert anodes will also eliminate anode effects, conditions of anode overvoltage that lead to emissions of the halocarbons CF₄ and C₂F₆. Although halocarbon emissions are small by weight, they have a much higher Global Warming Potential (GWP) and thus account for about one third of the carbon emissions from the current cell technology (Margolis). [At a typical proportion of 90% CF₄ and 10% C₂F₆, these emissions have an equivalent weighted average GWP of 6,770 compared to "1" for CO₂ (GWP is 6,500 for CF₄ and 9,200 for C₂F₆) (Gibbs and IPCC).]

Current Efforts: Since the early 1980s, the aluminum industry has done substantial R&D on "inert" anodes and "wetable" solid cathodes. The Department of Energy's Office of Industrial Technologies (OIT), has co-sponsored R&D on an advanced cell incorporating an inert anode, a wettable cathode and other important modifications to the Hall-Heroult process. Recently, the industry has demonstrated the technical and economic feasibility of a "wetable" solid titanium diboride-graphite (TiB₂) cathode in a prebaked cell. Preliminary results of short term tests of TiB₂-graphite elements inserted in production cell cathodes indicate potential reductions of up to 13% in energy consumption because the inter-electrode distance and thus the voltage was decreased substantially (Dillich 1997). Improved wettable cathodes depend upon materials development, process development and design. Another key technology in the advanced cell is an inert or "dimensionally stable" anode. With this type of anode, oxygen is evolved rather than CO₂ (as is carbon) during the electrolytic decomposition of Al₂O₃. Pilot scale tests are currently being conducted using a novel cermet material as the anodes and TiB₂ as the cathode. Progress on inert anodes depends upon advances in materials development and processes and cell design. This cell also features Bayer process improvements and advanced cell design and controls including electrode pack design, materials and controls for management of Heroult cells. Together, these technologies have the potential to reduce energy consumption during smelting by 27%. (Dillich 1997).

4.4.3.4 Replacing Cement Clinker with Solid Wastes

Potential: The cement industry is the single largest source of U.S. process CO₂ emissions and a major energy user. The annual process CO₂ emissions from the U.S. cement industry are 9-10 MMTce (EIA 1996). Energy related emissions are of similar magnitude depending upon the cement kiln technology. One technically straightforward and cost saving way to reduce energy input and carbon emissions per ton of cement is to replace some of the cement with abundant utility and steel plant waste. It is technically feasible to intergrind flyash (a waste product from the coal-fired utility industry), granulated blast-furnace slag (a waste product from the production of iron) or limestone into Portland cement. U.S. testing has shown that addition of up to 5% limestone (Livesay 1991) does not affect and may even improve product quality. European standards permit up to 35% intergrinding of limestone. However, U.S. product specifications (the Standard Specification for Portland Cement, ASTM C150) do not allow any extra ingredients in cements. Currently these specifications are difficult to change because a vocal minority (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 intergrinding could reduce both energy and process CO₂ 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 European owned 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 intergrinding materials and percentages and to ensure 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 million metric tons of carbon equivalent (MMTCe) of industrial carbon emissions could be avoided due to cement intergrinding and replacement.

Manufacturing Process: Portland cement is a finely-ground, manufactured, mineral product that, when mixed with water, sand, gravel and other materials, forms concrete, the most widely used construction material in the world. The raw materials are primarily limestone, shale, clay, and silica sand. They are crushed, proportioned to give the required chemical composition and ground. Small quantities of iron oxide and alumina are sometimes added to the raw mix. The mixture is heated to about 2700 °F (1500 °C) in large rotary kilns. The clinker, a hard granular intermediate product, is discharged from the kiln and finely-ground with about 5% gypsum as a setting time regulator to give cement. Carbon dioxide emissions in cement manufacturing come directly from combustion of fossil fuels and from calcining the limestone in the raw mix. On average, each ton of cement clinker produced results in the direct emission of one ton of CO₂. About 60% of the direct emissions are from calcination and the other 40% is from combustion products from fossil fuels that directly or indirectly supply the energy for calcination.

Industry Description: Though the manufacturing process has remained the same, the US cement industry 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 mmBtus in that year to 5.20 mmBtus in 1994. Most (>60%) of U.S. clinker capacity is foreign owned or affiliated with foreign firms. Most of these (20/29) 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 to 15% cement as a binder. Cement demand is projected to grow at 1% per year, half the rate of GDP.

Costs: 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 by replacing high cost clinker with these 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.

Environmental Sustainability: In addition to reducing CO₂ emissions, this technique also reduces NO_x, SO₂ and particulate emissions associated with electricity use. It also reduces solid waste by replacing quarried raw materials with wastes and by-products such as flyash, foundry sands and mine tailings.

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 industry 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. Some of the ways these objectives might be met are with the following technologies.

4.5.1.1 Black Liquor Gasification

The pulp and paper industry is a highly energy intensive industry but also one which generates a high fraction of its own energy. Traditionally, about 40% of the energy used in a mill is generated from burning the lignin solids. Lignin is that portion of the wood which 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. The steam is used to supply the mill's needs plus some is used to generate electricity for the mill. The energy efficiency of the electricity generation is about 25%.

In the black liquor gasification combined cycle (BLGCC) process a little less steam is generated to supply the mill but significantly more electricity is produced, 2-3 times more. Trends in process changes to make mills more environmentally friendly change the balance of energy forms that a mill uses. Mills are using less steam energy and more electrical energy; the BLGCC 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. If the new technology is implemented as these old boilers are retired, between approx. 2005 and 2020, it would represent approximately 8 gigawatts of installed power generation.

4.5.1.2 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 has led to significant effort 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 5 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 feedstocks. 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 feedstocks. 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, hexamethylenediamine, and dimethyl-terephthalate; 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)

4.5.3 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 feedstocks 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. The three major process areas which account for most of the energy usage in a refinery that could benefit from improvements in catalyst technology are: 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 roadmap is currently under preparation. These 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.

4.5.5 Aluminum

Many advanced technologies have been researched that could provide dramatic reductions in energy use in the aluminum manufacturing process. Because of the inherently high energy requirements of the Hall-Herault process, the most dramatic energy savings and emissions reductions are likely to result from new or improved smelting technologies. These include the development and commercialization of retrofit advanced cell technology with inert anodes and wettable cathode components.

4.5.5.1 Inert Anodes

Inert anodes offer a variety of advantages over traditional carbon anodes, including increased cell productivity, reduction in cell shorting due to undulations in the molten metal, and higher metal purity. 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). Energy savings from inert electrodes are estimated at 11%

over current production methods (Energetics 1990). In addition, inert anodes have the potential to substantially reduce CO₂ emissions during smelting.

4.5.5.2 Wettable Cathodes

Wettable cathodes have the potential to significantly reduce energy use in aluminum production. Because of reduction in cell shorting due to undulations in the molten metal and resulting reduction in anode-cathode distance, wettable cathodes can significantly reduce voltage drop at the cathodic aluminum interface. Potential energy savings are estimated as high as 15-20% over conventional cells (DOE 1990). Though most of the major aluminum producers have conducted research on titanium diboride cathodes, the high cost of production and early failure of the components have kept them from commercialization.

4.5.6 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. The sections below 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 ironmaking processes that are under development. R&D effort should focus on developing a process scheme that incorporates both ironmaking and steelmaking 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 steelmaking operations and simultaneously produce power in a combined cycle that includes both gas and steam turbines.

Steelmaking 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.

4.5.7 Metal Casting

A diverse group of CEOs and presidents from the foundry, diecasting, 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.

4.5.7.1 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 saving of 130,000 tons per year, with an associated energy savings of 25 trillion BTUs 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, that is 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, the 1997 Annual Energy Outlook. 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 which project that 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 two and a half quads in the high case. The LIEF model projects that these reductions could arise from cost effective investments defined by a capital recovery factor (CRF) of 15%; about a 7 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 examples are technologies which 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 requires 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. Therefore, these 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 sized 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 demonstrations focuses on lowering 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, their current business and technical practices, as well as current domestic and international market conditions.

For all of these industries discussed above, further progress in energy efficiency beyond 2010 requires further developments in technology. These developments may be *incremental* improvements, for example sensors, controls, and system/process modeling, or may be *fundamental* breakthroughs, for example catalysts, direct smelting, or bio-processing. Incremental improvements need not be associated with 'small' efficiency changes. The ability to sense and adjust a process to achieve optimal operating condition 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 4.7 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. It should be noted that the year 2010 designates currently (or very near commercial) technologies, while the year 2020 designates technologies that will require further R&D, not any 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 4.7 Summary of Technology Examples

Example Taken From	Technology Example	Year	Type of change	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	Titanium Diboride Cathodes	2010*	I	N	E
Aluminum	Inert Anodes	2010*	I	N	E
Aluminum	Aluminum Chloride Process	2020	F	N	E
Aluminum	Carbothermic Reduction Process	2020	F	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	Cogeneration	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	Multipoint 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 4.4.

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ENDNOTES

¹ Differences in the industry sub-sector 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.

² 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. There are rapidly penetrating technologies such as sensors and process control software and technology that can save significant amounts of energy.

³ The forest products industry include 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.

⁴ In particular, we do not change the underlying forecast for activity in the refining sector.

⁵ These numbers are calculated from the numbers shown in Appendix A for Figure 16, DOE 1995.

⁶ Authors calculation based on penetration data in (Boyd, Molburg and Thimmapuram, 1996). The food industry is typical of the average kWh/Btu cogenerated in the US. Paper and chemical cogenerate about 50% more than average. The assumption that only regions/industries whose generation is between 50% and 100% of the US average can increase their utilization is a simple attempt to rule out those regions or industries whose energy prices or steam usage patterns tend to preclude higher rates of cogeneration. We did not consider that new technology might increase electric output in those sectors with high rates of implementation, which is also possible with better technology.

From: Richard Sextro (6/11/97)
To: Ann Skirry

Mail*Link® SMTP meeting with space czars
Ann'-- Don and I would like to meet with the space folks. Could you set
up something for us? My version of MM (do you have a proxy for me) is
pretty up to date. Here are the names, etc. (extracted from a Lisa
Sullivan email):

- Kirk Haley (x5973) will take over as lead of the Space Team. As a
Facilities Planner he will work with each of your divisions on long range
space planning.
- Shana Salter (x6632) , Planning Associate, will tackle your day to day
space requests.

Thanks very much
-- Rich

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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 percent per year (U.S. DOE/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 percent 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).
- 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).
- During 1970-1994, the energy intensity of rail freight decreased from 691 Btu/ton-mile to 388 Btu/ton-mile, or 44 percent (Davis and McFarlin, 1996, Table 2.17).

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 percent of the period's MPG gain was achieved by shifts to smaller cars (Westbrook and Patterson, 1985). Between 1976-1989, the combination of weight reduction, improved transmissions, tires, and aerodynamics, widespread use of fuel injection,

¹This 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.

various engine improvements, improved lubricants, and wider use of front wheel drive accounted for about 70 percent 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 percent of the improvement in rail freight energy efficiency came from increased loadings per car, much of the 85 percent 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 percent (Greene, 1996).

Over the past ten years (1986-1996), the rate of growth of transportation energy use has averaged 1.6 percent per year, but in the past three years it accelerated to 2.2 percent 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 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 percent 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 roughly equal to that of GDP and modest to no improvement in energy efficiency.

Despite these recent trends, the 1997 Annual Energy Outlook (AEO) Reference Case Forecast to 2015, which serves as the backdrop for this analysis, foresees very slow growth in transportation energy use (1.4 percent/yr.) accompanied by virtually no change in the prices of transportation fuels (0.2 percent/yr.). A modest rate of growth in vehicle travel (1.4 percent/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 percent 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" 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 is actually an incarnation of a 20 year old federal R&D effort in advanced automotive technologies established originally by the Energy Policy and Conservation Act of 1975 and the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976. Current PNGV spending is a few hundred 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-CO₂ 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, 1997 AEO version, with Reference Case assumptions about macroeconomics and energy prices (Decision Analysis Corp., 1996; U.S. DOE/EIA, 1994). These are labeled the (1) "business-as-usual," (2) "efficiency," and (3) "high efficiency/low carbon" cases. Our "business-as-usual" case differs from the 1997 AEO Reference Case only in that new light-duty vehicle fuel economy is held constant at current levels throughout the period of the forecast.

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The two higher-than-baseline efficiency 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 they are a likely outcome of such an intensification.

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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 NEMS Reference Case. 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 the 1997 AEO forecasts cheap, 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.

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 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 versus 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.

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 1997 AEO 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 percent in 2010 and 33 percent higher by 2015. The "efficiency" scenario achieves roughly a 10 percent reduction in energy use and a 12 percent reduction in transportation sector emissions versus the "business-as-usual" case by 2010. Reductions in 2010 versus the EIA 1997 Reference Case are slightly less, 7 percent for energy and 9 percent for carbon emissions. Use of cellulosic ethanol as a blending component in gasoline reduces greenhouse gas emissions by 2-3 percent over and above the reduction in energy use. The greatest reductions in fossil fuel use are achieved by rail freight (-16 percent), light-duty highway vehicles (-12 percent) and commercial air travel (-11 percent). 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 percent below the "business-as-usual" case but still 10 percent over 1997 levels. Emissions of carbon are down by 20 percent over the "business-as-usual" case, still 6 percent higher than in 1997. The "high efficiency/low carbon" scenario reduces energy use and carbon emissions by another 4 percent in 2010 and by an additional 5 percent 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 EIA's 1997 Reference Case

	Energy Use (Quadrillion Btu)		
	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 (Million Metric Tons of Carbon)			
	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 it 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, automakers 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., *Documentation of the Fuel Economy, Performance, and Price Impact of Automotive Technology*, Prepared for Martin Marietta Energy Systems, July, 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 ranging from a "clean sheet" design using advanced steel alloys that might achieve greater than a 10 percent weight reduction in a mid-sized auto, to all-aluminum vehicles using successively more optimized designs achieving up to a 30 percent reduction, to a technically-optimistic design using polymer composites achieving a 35-40 percent 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 percent 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 percent 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_d s) 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 percent reduction in C_d typically will yield a 2.0-2.5 percent increase in fuel economy at constant performance.

Prototypes with extraordinarily low C_d s (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 automakers, however, that mass market vehicles will likely be limited to C_d s of about 0.25 because of limits on the

²This 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.

practical slope of windshields, need for cargo space (low C_d s require tapered rear ends), and other factors, including customer design preferences. Further, reductions in C_d s 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.

how does shift to move trucks affect this
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 percent 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 percent 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 to 3 MPG range (Hattori et al., 1990). A number of continuously variable transmissions (CVTs) have been tested with widely varying results, and Subaru 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 percent 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 percent 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 percent 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 2 rings instead of three
- improved oil pumps
- improved lubricants
- low friction crankcase seals
- roller cam followers.

Only roller cam followers and two-ring pistons are discrete technologies, with specific benefits

of 2 percent in fuel economy, while other benefits are based on design evolution.

Fuel economy improvements of as much as 4.5 percent (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 percent 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 percent 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, MIVEC, 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 percent.

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 (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 sparkplug 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 percent 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 percent reduction in rolling resistance and a 3-4 percent 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 percent reduction in rolling resistance by 2005, with 5 percent improvement in fuel economy resulting; an additional 3 percent 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 4 discrete steps over time to achieve a total 4 percent 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 powertrains
- Direct injection stratified charge (DISC) gasoline engines
- Direct injection (DI) diesel engines
- Proton exchange membrane (PEM) fuel cell powertrains

All but the PEM fuel cell powertrains 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. Currently, however, diesels have an exemption to U.S. rules on NO_x emissions, an exemption that is unlikely to stand if large numbers of diesels are sold in the U.S. market and DI diesels cannot meet current NO_x standards for gasoline-fueled automobiles. 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 automakers. Some existing vehicle designs that have attained lower C_d s 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 percent reduction in drag over the lowest C_d value in NEMS of 0.245.

5.2.9 Hybrid-Electric Powertrains

Hybrid-electric powertrains 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, untracapacitor, etc.). Hybrids offer a theoretical efficiency advantage over conventional internal combustion engine (ICE) drivetrains because:

- 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, with the electric energy produced stored in the battery or other storage device, and
- 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 percent 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 generally are 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

³The 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 it 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).

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 percent 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 requirements⁴ 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 percent fuel economy benefit over a 1995 conventional gasoline-fueled car, and a 10 percent benefit over a DI diesel vehicle for the efficiency case; in the high efficiency/low carbon case, the assumed gains are 43 percent and 23 percent, 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 (1 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

⁴In particular, requirements for 0-60 mph acceleration and sustained gradeability.

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 suggests that Toyota's DISC engine provides a 25 percent fuel economy benefit in the Japanese 10-mode cycle, which could translate to an 18 percent 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 percent is assumed.

5.2.11 Turbocharged Direct Injection (TDI) Diesel Engines⁵

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 percent or more over current 2-valve per cylinder engines, though conversion to gasoline equivalent fuel economy yields closer to a 30 percent gain (diesel fuel is a more energy-dense fuel than gasoline). The 40 percent value has been used in our analysis, but it assumes that

⁵Also referred to as compression ignition direct injection (CIDI) engines and turbocharged direct injection (TDI) diesel engines.

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 percent 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/cm² in 1990 to current levels of about 0.15 mg/cm²) (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

⁶An 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.

⁷At about 3700 psi storage pressure, storage volume for hydrogen is about 5 times that needed for gasoline (Oei, 1997).

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 timeframe, 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 automakers 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 percent 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

⁸An additional Acost@ 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.

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 percent to 40 percent. The drive-cycle thermal efficiency of current methanol steam-reforming fuel cell drivetrains (including electric motor/controller and battery) is also 35 percent to 40 percent. 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 percent to 50 percent, 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 percent of the time for local service locomotives and over 50 percent of the time for line-haul. Idle fuel consumption accounts for 38 percent of fuel consumed in local service locomotives, and only 6.3 percent of fuel consumed for line-haul locomotives (CARB, 1991;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 8 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 10 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 powerplants are clearly very different, presumably a portion of any cost reductions achieved in automotive fuel cell 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 percent). Fuel savings of 40 percent 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 8 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 percent market share by 2010, and 16 to 18 percent by 2015, for the total fleet. In the high efficiency/low carbon scenario, we assume a 5 percent share in 2010 and 20 percent 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 have analyzed cost reductions based on cumulative total production, and concluded that many new technologies experience a 20 to 35 percent 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 5 to 7 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 percent over the next decade. We have utilized the data from the Lipman and Sperling paper to conclude that a 30 percent cost reduction over the 1997-2005 period is possible relative to the costs derived for OTA.

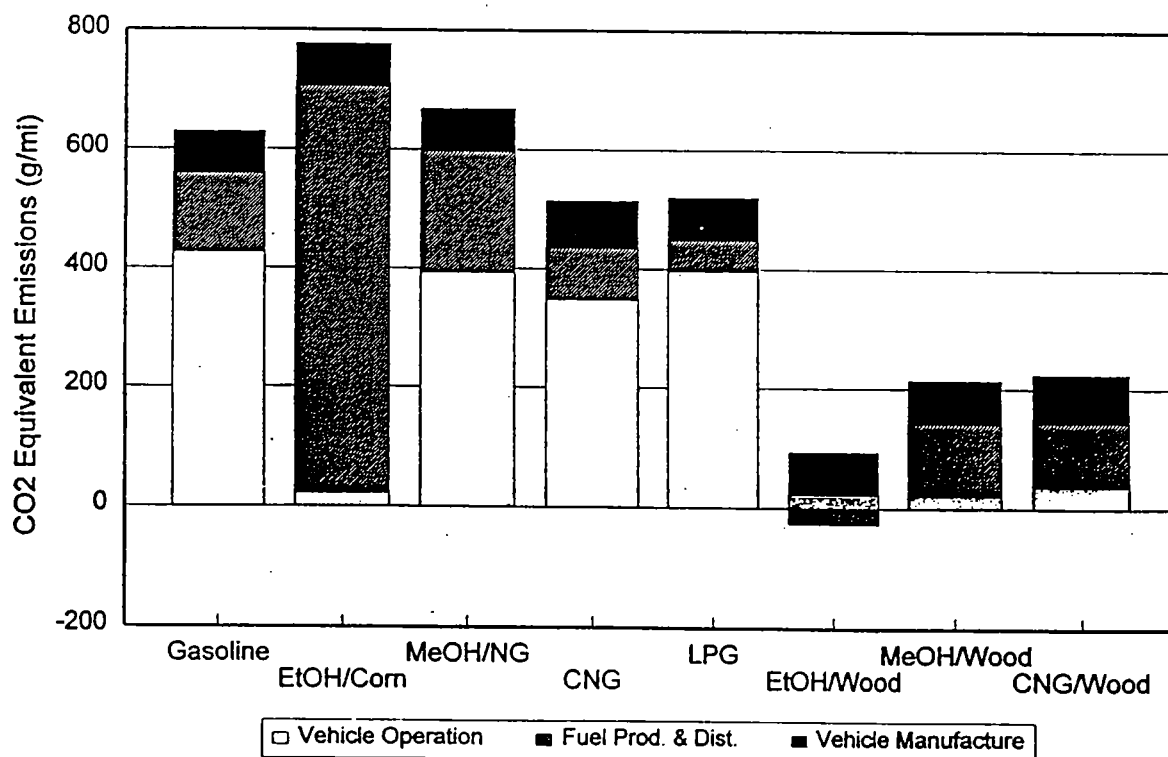
A second factor is the timing of technology introduction. The contrast here is between new technology introduction in a "business-as-usual" scenario relative to one where both business and government invest in research and development at rates consistent with an accelerated PNGV, coupled with changes in market preferences for fuel economy. The resulting reduction in lead time is assumed to be 30 percent 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 ($1996 + [13 \times 0.7]$) 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

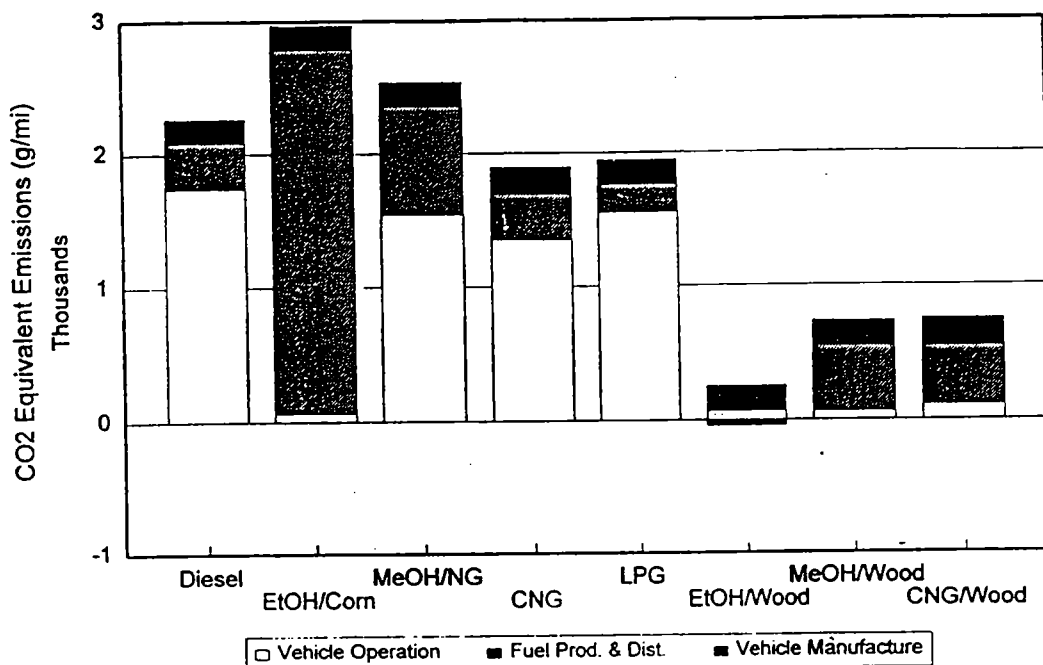
Alternative Fuels derived from fossil energy sources have limited potential to reduce greenhouse gas emissions. The full fuel cycle greenhouse gas emissions of fossil fuels have been compared in detail by Delucchi (1991, tables 9a, 9b, 9d, 9e), Wang (1996) and others. Several fossil fuel alternatives have somewhat lower CO₂ 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 CO₂ 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 CO₂ reduction potential.

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



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

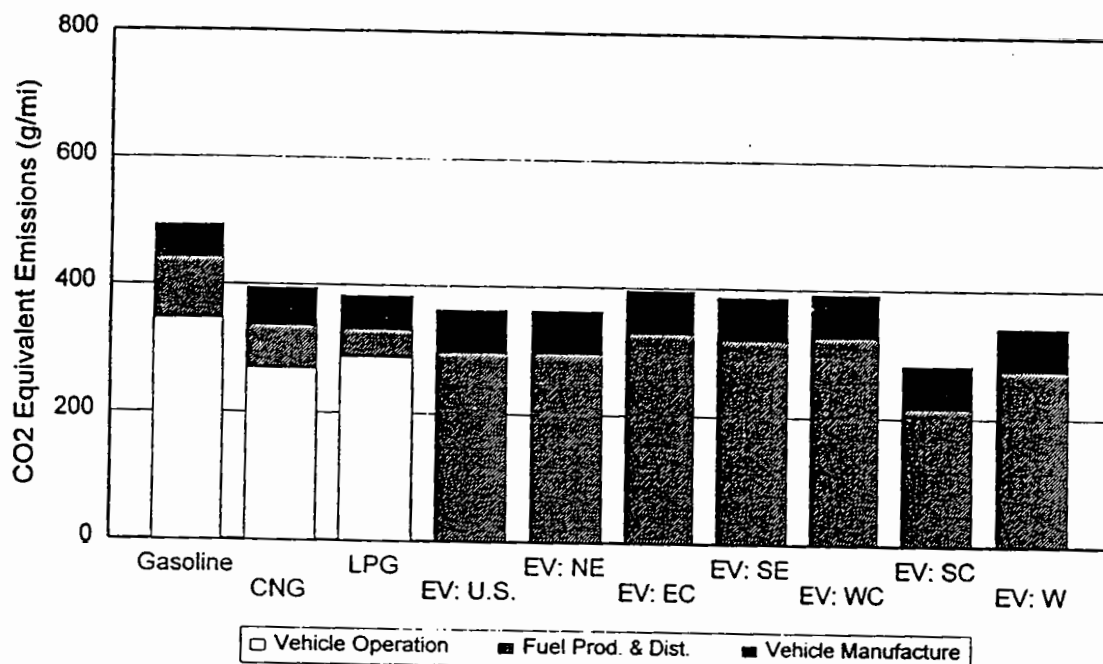
Figure 5.2 Fuel Cycle Greenhouse Gas Emissions: Heavy-Duty Vehicles



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

Battery-powered electric vehicles 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 CO₂ 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 CO₂ 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 5.3 Projected Fuel Cycle Greenhouse Gas Emissions of Battery-Powered Electric Vehicles by Region in 2015



Source: February, 1997 estimates prepared by Mark Delucchi, obtained by personal communication from Margaret Singh, Argonne National Laboratory, Washington, D.C., May 19, 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 ELA's 1997 AEO 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, the 1997 AEO 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 1997 AEO 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 1997 AEO 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 (U.S. DOE/ELA, 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 CO₂ 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 percent 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, ch. 4.3).

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, ch. 3). 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 CO₂ 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

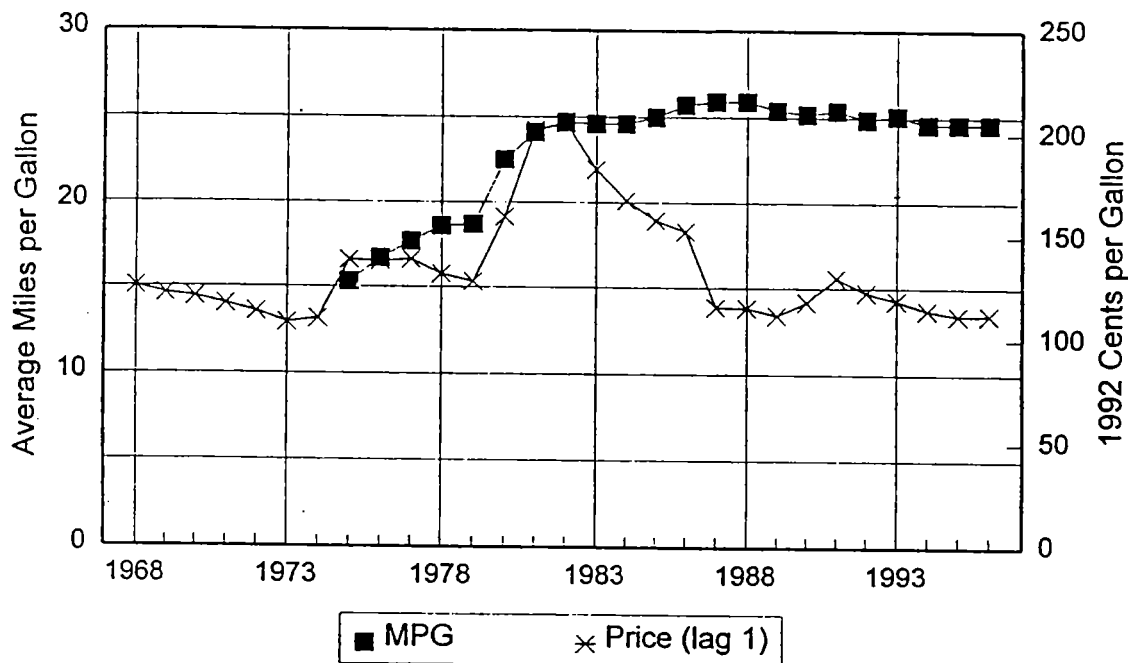
The EIA 1997 AEO Reference Case serves as the "business-as-usual" case, except for its forecast of increasing light-duty vehicle MPG through 2015. The EIA's AEO Reference Case projects an increase in passenger car MPG from 27.5 in 1997 to 31.5 in 2010 and 32.6 in 2015. Light truck MPG is projected to 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, or as they were in the early 1970s prior to the first oil price shock. Given that the 1997 AEO 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. From a purely technical modeling perspective,

however, the NEMS fuel economy subroutines tend to adopt fuel economy technology that is presented to them. They will even adopt technologies that are less than cost-effective, albeit at a much lower level of market penetration than cost-effective technologies. Because a significant slate of current and future fuel economy technologies are represented in the Reference Case input data, the model makes use 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.

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

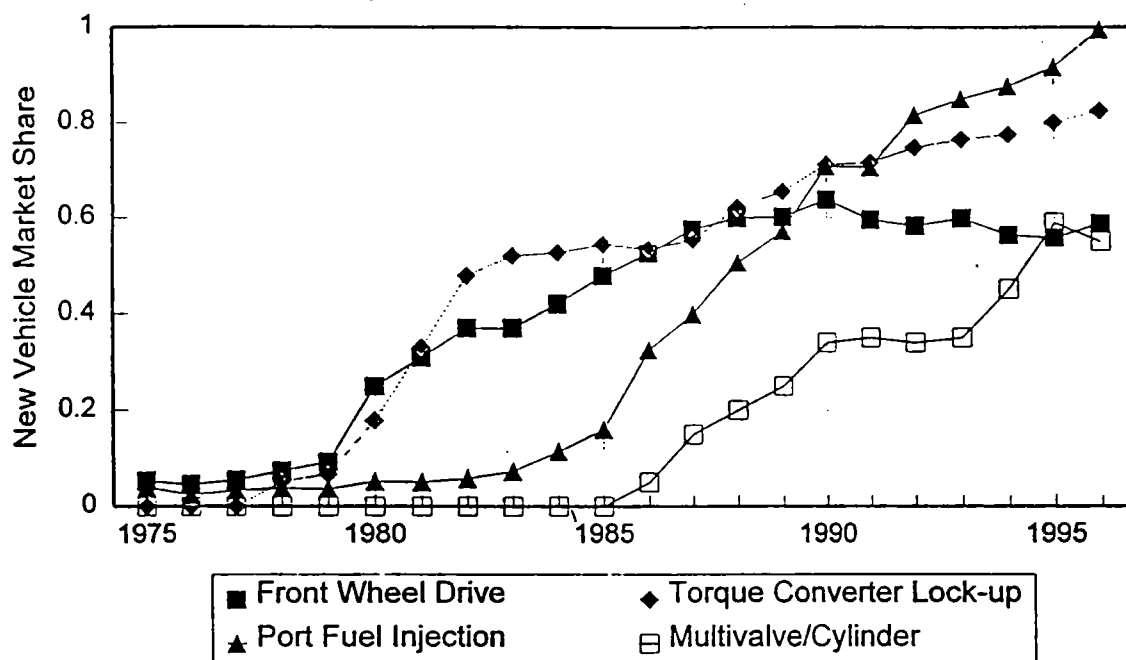


Sources: Heavenrich and Hellman, 1996, table 1; U.S. DOE/EIA, Ann. Energy Rev. 1995, table 5.21.

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 5.4). 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 percent and weight by 13 percent 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.

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



Source: Heavenrich and Murrell, 1996, table 1.

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 EIA base 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.

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 times to market introduction for advanced technologies can be reduced by 25 percent by 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 include:

- 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),
- 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 for technical reasons that have to do with the structure of the NEMS model. In preparing the technology list for NEMS, it is the analysts' responsibility to insure that technologies are truly distinct and different. If the same technology were listed twice by mistake, NEMS would assume that two entirely different technologies were available to improve fuel economy and would use them both equally. By excluding the diesel hybrid we are, in effect, asserting that the gasoline and diesel hybrids are too similar to be considered different technologies. Reality is obviously somewhere in between. 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. The 2-stroke engine, on the other hand, was left off the "efficiency" scenario list to reduce the number of engine technologies manufacturers would have to accommodate. Again, it is partly the analyst's responsibility to see that the extent of change demanded of manufacturers is reasonable. 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. 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 also assumes a 30 percent reduction in costs for certain key technologies.

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 percent efficiency improvement for heavy trucks,
- reduced empty weight,
- the turbo compound diesel engine, and
- advanced drag reduction.

For commercial aircraft, an efficiency improvement of 40 percent was projected for 2015 for new aircraft, comprised of 25 percent engine efficiency gains and 15 percent aerodynamics and materials substitution. Also, load factors were assumed to increase to 70 percent 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 percent per year, actually somewhat lower than the 2.8 percent/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 NEMS Reference Case set. 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 v. light trucks, domestic v. imported, and four size classes. 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 percent of the light trucks did (Heavenrich and Hellman, 1996). One hundred percent of passenger cars and 99 percent of light trucks had port fuel injection, and so on. 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 Scenarios

Technology	MPG Benefit (%)	Price Increase	Weight (lbs.)	Introduction Date	Notes
DISC	16	\$300	50	2000	Reduces benefit of variable valve technology by 50%
Turbo DI Diesel	40	\$1100	125	2004	Incompatible with variable valve technology
Hybrid/Gasoline	28/43	\$3000	250	2005	Incompatible with VVT
Hybrid/Diesel	54/72	\$3500	350	2005	Incompatible with VVT. Included in only the High Efficiency scenario.
Drag VI	11.5	\$256	60	2012	

efficiency scenario/high efficiency scenario

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. The reference case discount rate is 8 percent per year and the payback period is 4 years. This was changed to a 7 percent real discount rate over 5 years in order to equate the total discounted lifetime miles to a vehicle with an expected life of 14 years, using an annual real discount rate of 20 percent.

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 percent 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 EIA 1997 AEO 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 dollars). Such variations are within the noise of

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

	2010	2015
Technology	Fuel Economy Improvement (%)	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%	123%

1997 MPG
27.5

2010 MPG

2015 MPG

Maximum Use of All Fuel Economy Technology

	55.0	61.3
Percent Improvement	100%	123%

New Car Salesweighted Average Fuel Economy: Low CO₂ Scenario

	37.5	41.4
Percent Improvement	36%	51%

New Car Salesweighted Average Fuel Economy: Breakthrough Scenario

	43.1	50.2
Percent Improvement	57%	83%

improvements if cost-effective reductions in CO₂ emissions are to be realized.

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 (U.S. DOE/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 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 percent (or even 10 percent) 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. Further increases in performance (horsepower/weight) predicted by the NEMS model are not considered, 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 percent to 55 MPG in 2010, and by another 20 percent 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.

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

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 1997 AEO 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 percent should be possible, with a consequent 3 percent increase in fuel economy (Roberts and Greene, 1983; Greene, 1996a, Ch. 5, Table 5.5). Reduced empty weight is assumed to be applicable to all types of heavy trucks.

The 1997 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 percent to 10 percent 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 1997 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 percent 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 1997 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 1997 Reference Case assumed that the LE-55 engine would have a maximum market potential of 50 percent for heavy-duty diesels. The "efficiency" scenario assumes a 100 percent maximum for heavy

⁹Despite 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.

diesels, but only 50 percent for heavy gasoline, LPG, and CNG trucks. Likewise, the maximum market potential for other advanced technologies were increased to 100 percent 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 percent, 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 Key Heavy Truck Fuel Economy Technologies for 2010

Technology	Year of Introduction	Trigger Price (1995\$ per 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%
Improved Tires II	2005			
Reduced Empty Weight	1997	\$7.75	90% / 100%	3%

5.3.2.7 Changes to the Rail Model

The NEMS Reference Case scenario assumes an annual rate of reduction in rail freight energy use per ton-mile of 1 percent. Since 1972, the average annual rate of reduction in energy use per ton-mile has been 2.8 percent 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 part to use of advance 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. Advanced technologies that can play a role in substantially reducing rail energy use in the future include the following (adapted from Cataldi, 1995).

- **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 CO₂ 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 percent annual improvement in ton-mile efficiency in the "efficiency" case compared with the 1 percent rate assumed in the 1997 AEO 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 percent by the 2010 to 2015 time period, to be achieved through a combination of improved propulsion system performance (25 percent) and aerodynamic and weight improvements (15 percent) (NRC, 1992, p. 49).

Once again, in the NEMS 1997 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 turbofans, 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 percent.

Finally, the NEMS 1997 Reference Case predicts no changes in aircraft load factors. Aircraft industry analyses foresee commercial load factors increasing to 70 percent 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 very likely will 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 percent by 2015 while the 1997 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 CO₂ 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. 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 percent net reduction in greenhouse gas emissions per mile (Figure 5.3).

In the context of this analysis, a 20 percent 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 metric ton of carbon, this could justify up to a \$0.06 to \$0.12 per gallon subsidy¹⁰ for a fuel that produced no greenhouse gas emissions. A 20 percent reduction, therefore would 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, ch. 3). 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 feedstocks can yield significant reductions in greenhouse gas emissions. The most recent estimates indicate that ethanol derived from cellulosic feedstocks (as opposed to grain) produces less than 1 percent as much greenhouse gas emissions on a fuel cycle basis as conventional gasoline or diesel fuels (Singh, 1997¹¹). 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 feedstock 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

¹⁰For carbon only; or \$0.08-\$0.16 per gallon if the tax applies to all greenhouse gases, on a carbon equivalent basis.

¹¹Communication 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.

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 feedstocks 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, to corn-based ethanol's disadvantage in greenhouse gas emissions, but future widespread use of corn stillage as fuel would swing ethanol's greenhouse 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 percent 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.

and

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: M. Singh, Argonne National Laboratory, April 3, 1997.

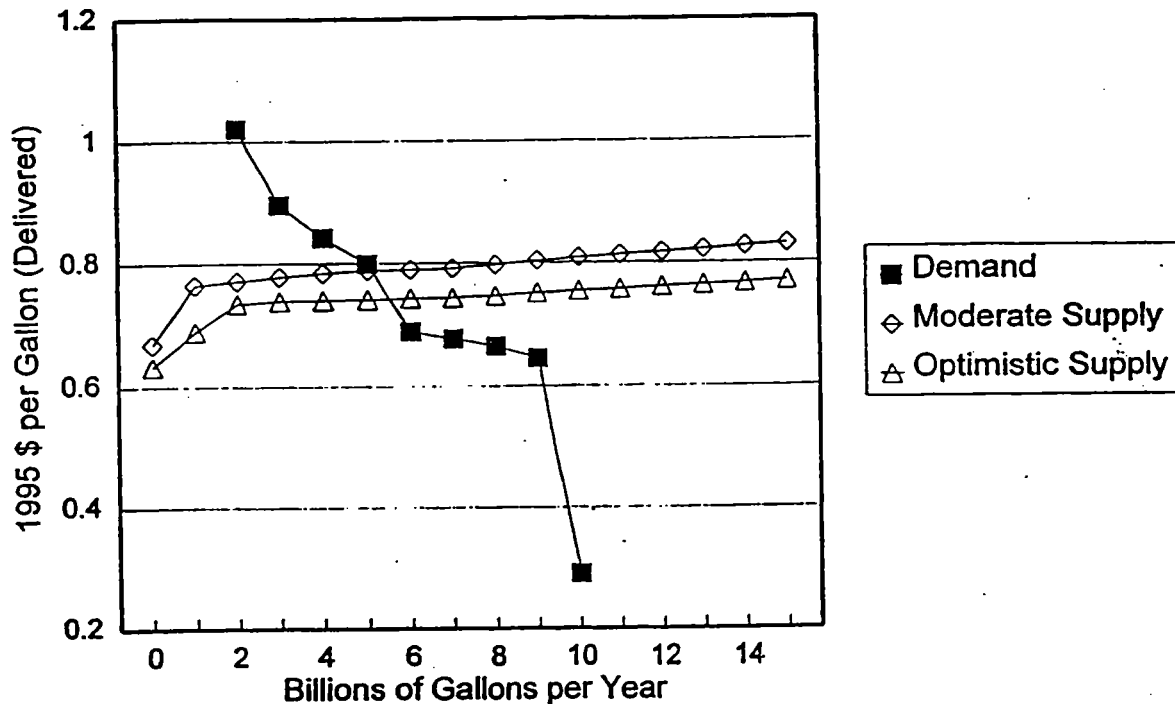
Initial estimates of the cost of ethanol produced by the NREL process ranged from \$0.78 to \$1.27 (1990 \$) per gallon, plant gate price (Chem Systems, 1993, Tables II-9 to II-13). However, recent cost projections (Bowman, et al., 1997) based on a comprehensive assessment of

feedstock 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 feedstocks: 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 feedstocks 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 (U.S. DOE/EIA, 1996a, Tables 5.20 and 5.21). Because ethanol has only about 2/3 the energy content of gasoline, the comparable price of ethanol per gasoline energy equivalent gallon would be \$1.63 for the first billion gallons, \$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 percent. 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 metric tons of carbon equivalent in 2010 versus 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 tons of carbon, while the emissions before and after are in tons of CO₂.

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 metric ton CO ₂ per year)	46.6	62.2
GHG Emissions After (million metric tons CO ₂ per year)	0.3	0.4
GHG Emissions Reduction (million metric tons C per year)	12.6	16.8

How much
land is
required
to generate
this?

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, NEMS is unaware that they require diesel fuel instead of gasoline.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 one percent.

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.

¹²An 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 a 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.

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 percent 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. Since 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. *how is this calculated*

how do they get this #

Some of the technologies necessary to produce an 84 percent 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 percent and 72 percent, respectively. A more optimistic assumption is made for the DISC engine, as well. Its fuel economy benefit is increased to 23 percent from 18 percent.

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 percent 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.

[Handwritten star symbol]

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 A). These were left out of the high efficiency/low CO₂ 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.

Box A. Another Potential Breakthrough Technology

Aside from the new technologies postulated in the high efficiency/low CO₂ scenario, other potential technologies could yield substantial reductions in greenhouse 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 percent in 2015, with power generation heavily weighted to coal; whereas Wang (1997) estimates a 19 percent 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-CO₂ 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
- Electric motors—especially, higher efficiency over a range of driving cycles, 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 percent reduction in greenhouse gases compared to gasoline use in 2015, whereas Wang (1997) estimates a 5 percent *increase* in 2005. The primary difference in the two analyses is that Wang computes a 10 percent energy efficiency penalty associated with switching to CNG, based on recent test data; Delucchi estimates an 11 percent 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 CO₂ 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 percent 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 percent penetration for each technology by 30 percent. 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 percent efficiency improvement over high bypass turbofan engines, and 10-15 percent 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 percent or more, only a 9 percent 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 percent efficiency gain, thermodynamic improvements provide a 15 percent gain, and advanced aerodynamics yield an 18 percent improvement. In this case, those are increased to 17 percent, 18 percent and 27 percent, respectively, certainly optimistic but not implausible estimates (see, e.g., Greene, 1992, Table 4).

The annual efficiency improvement rate for railroads is increased to 2.5 percent, still slightly lower than the 2.8 percent rate achieved over the past two decades. Waterborne freight's efficiency improvement rate is bumped up to 1 percent per year from 0.05 percent to reflect a 10 percent 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 percent by 2010 and by 18-25 percent 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.

The 23 percent gain for light-duty vehicles in 2015 is just slightly higher than the 21 percent and 22 percent improvements by freight trucks and rail in the "efficiency" scenario. Aircraft efficiency gains seem to lag behind at a mere 9 percent in 2015, but this is due to the fact that air passenger efficiencies increase the most (17 percent) 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.

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 percent from 1997 to 2010, an average annual rate of just 1.5 percent. In the "high efficiency/low carbon" scenario, the increase is 24 percent, reflecting a very small increase due to the lower fuel cost per mile of vehicle travel (1.7 percent/year). Growth from 2010 to 2015 is slower still, 1.1 percent per annum. Air travel is the fastest growing mode, with seat-miles growing at 3.4 percent annually through 2010 and slowing to 2.1 percent 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 percent lower in the "efficiency" case than in the Business-as-Usual Case in 2010 (Tables 5.6 and 5.7). Freight truck vehicle miles increase at a faster rate than light-duty vehicle miles, 2.5 percent per year through 2010, slowing to 1.1 percent 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 percent and 17 percent, respectively by 2010. Once again, the growth rate from 2010 to 2015 is at the much slower rate of about 1 percent per year.

Table 5.7 Transportation Sector Energy Use and Energy Efficiency Projections to 2010 and 2015

	1997		2010		
	Base Case	Base Case	Efficiency	Change	%
Energy Use (Quads)	25.49	32.33	29.26	-3.07	-9%
Carbon Emissions (MMT C/Yr.)	486.9	615.9	543.3	-72.6	-12%
Fuel Use by Fuel Type (Quads)					
Motor Gasoline	15.08	18.02	15.23	-2.79	-15%
Cellulosic Ethanol (in motor gasoline)	0.00	0.00	0.46	0.46	***
Distillate	4.56	5.78	5.65	-0.13	-2%
Jet Fuel	3.55	4.67	4.16	-0.51	-11%
Residual	1.17	1.64	1.64	0.00	0%
Other	1.13	2.22	2.13	-0.09	-4%
Energy Use by Mode (Quads)					
Light-Duty Vehicles	14.63	18.21	16.27	-1.94	-11%
Freight Trucks	5.55	6.80	6.27	-0.53	-8%
Air	3.59	4.71	4.20	-0.51	-11%
Rail	0.48	0.51	0.43	-0.08	-16%
Marine	1.74	2.30	2.30	0.00	0%
Pipeline	0.75	0.88	0.88	0.00	0%
Other	0.23	0.29	0.29	0.00	0%
Energy Efficiency Indicators					
New Car MPG	27.5	27.8	37.5	9.70	35%
New Light Truck MPG	20.5	20.6	27.1	6.50	32%
Light-Duty Fleet MPG	19.6	19.4	21.5	2.10	11%
Aircraft Efficiency (Seat-Miles/Gal.)	51.8	58.2	61.6	3.40	6%
Freight Truck Fleet MPG	5.6	6.0	6.8	0.80	13%
Rail Efficiency (ton-miles/1,000 Btu)	2.7	3.0	3.6	0.60	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.

Table 5.7 Transportation Sector Energy Use and Energy Efficiency Projections to 2010 and 2015
(Continued)

	1997		2015		
	Base Case	Base Case	Efficiency	Change	%
Energy Use (Quads)	25.49	33.96	28.72	-5.24	-15%
Carbon Emissions (MMT C/Yr.)	486.9	646.0	531.8	-114.2	-18%
Fuel Use by Fuel Type (Quads)					
Motor Gasoline	15.08	18.72	13.47	-5.25	-28%
Cellulosic Ethanol (in motor gasoline)	0.00	0.00	0.43	0.43	***
Distillate	4.56	6.00	6.47	0.47	8%
Jet Fuel	3.55	4.95	4.22	-0.73	-15%
Residual	1.17	1.78	1.78	0.00	0%
Other	1.13	2.51	2.35	-0.16	-6%
Energy Use by Mode (Quads)					
Light-Duty Vehicles	14.63	19.07	15.50	-3.57	-19%
Freight Trucks	5.55	7.07	6.25	-0.82	-12%
Air	3.59	5.00	4.27	-0.73	-15%
Rail	0.48	0.51	0.41	-0.10	-20%
Marine	1.74	2.46	2.47	0.01	0%
Pipeline	0.75	0.93	0.93	0.00	0%
Other	0.23	0.30	0.30	0.00	0%
Energy Efficiency Indicators					
New Car MPG	27.5	27.9	41.4	13.50	48%
New Light Truck MPG	20.5	20.6	31.9	11.30	55%
Light-Duty Fleet MPG	19.6	19.5	24.0	4.50	23%
Aircraft Efficiency (Seat-Miles/Gal.)	51.8	60.6	66.1	5.50	9%
Freight Truck Fleet MPG	5.6	6.1	7.4	1.30	21%
Rail Efficiency (ton-miles/1,000 Btu)	2.7	3.2	3.9	0.70	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 Energy Use and Energy Efficiency Projections to 2010 and 2015

	1997		2010		
	Base Case	Base Case	High Efficiency /Low Carbon	Change	%
Energy Use (Quads)	25.49	32.33	27.88	-4.45	-14%
Carbon Emissions (MMT C/Yr.)	486.9	615.9	511.5	-104.4	-17%
Fuel Use by Fuel Type (Quads)					
Motor Gasoline	15.08	18.02	13.87	-4.15	-23%
Cellulosic Ethanol (in motor gasoline)	0.00	0.00	0.65	0.65	***
Distillate	4.56	5.78	5.65	-0.13	-2%
Jet Fuel	3.55	4.67	4.01	-0.66	-14%
Residual	1.17	1.64	1.64	0.00	0%
Other	1.13	2.22	2.05	-0.17	-8%
Energy Use by Mode (Quads)					
Light-Duty Vehicles	14.63	18.21	15.21	-3.00	-16%
Freight Trucks	5.55	6.80	6.17	-0.63	-9%
Air	3.59	4.71	4.06	-0.65	-14%
Rail	0.48	0.51	0.38	-0.13	-25%
Marine	1.74	2.30	2.28	-0.02	-1%
Pipeline	0.75	0.88	0.88	0.00	0%
Other	0.23	0.29	0.29	0.00	0%
Energy Efficiency Indicators					
New Car MPG	27.5	27.8	43.1	15.30	55%
New Light Truck MPG	20.5	20.6	30.8	10.20	50%
Light-Duty Fleet MPG	19.6	19.4	23.2	3.80	20%
Aircraft Efficiency (Seat-Miles/Gal.)	51.8	58.2	64.6	6.40	11%
Freight Truck Fleet MPG	5.6	6.0	7.0	1.00	17%
Rail Efficiency (ton-miles/1,000 Btu)	2.7	3.0	4.0	1.03	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.

Table 5.8 Transportation Sector Energy Use and Energy Efficiency Projections to 2010 and 2015 (Continued)

	1997		2015		
	Base Case	Base Case	High Efficiency /Low Carbon	Change	%
Energy Use (Quads)	25.49	33.96	26.67	-7.29	-21%
Carbon Emissions (MMT C/Yr.)	486.9	646.0	484.4	-161.6	-25%
Fuel Use by Fuel Type (Quads)					
Motor Gasoline	15.08	18.72	11.22	-7.50	-40%
Cellulosic Ethanol (in motor gasoline)	0.00	0.00	0.72	0.72	***
Distillate	4.56	6.00	6.74	0.74	-12%
Jet Fuel	3.55	4.95	4.00	-0.95	-19%
Residual	1.17	1.78	1.77	-0.01	-1%
Other	1.13	2.51	2.22	-0.29	-12%
Energy Use by Mode (Quads)					
Light-Duty Vehicles	14.63	19.07	13.84	-5.23	-27%
Freight Trucks	5.55	7.07	6.18	-0.89	-13%
Air	3.59	5.00	4.06	-0.94	-19%
Rail	0.48	0.51	0.31	-0.20	-38%
Marine	1.74	2.46	2.43	-0.03	-1%
Pipeline	0.75	0.93	0.93	0.00	0%
Other	0.23	0.30	0.30	0.00	0%
Energy Efficiency Indicators					
New Car MPG	27.5	27.9	50.2	22.30	80%
New Light Truck MPG	20.5	20.6	37.8	17.20	83%
Light-Duty Fleet MPG	19.6	19.5	27.1	7.60	39%
Aircraft Efficiency (Seat-Miles/Gal.)	51.8	60.6	70.7	10.10	17%
Freight Truck Fleet MPG	5.6	6.1	7.5	1.40	23%
Rail Efficiency (ton-miles/1,000 Btu)	2.7	3.2	4.8	1.63	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%

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 percent in 2010 and carbon emissions by an additional 3 percent, due to the success of cellulosic ethanol as a gasoline blending component. Still, energy use is up 15 percent over the 1997 level, and carbon emissions are 12 percent higher. In 2015, however, energy use and carbon emissions are reduced versus 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 quad lower than the current level in 2015. The use of 0.4 quad 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-CO₂" scenario achieves the milestone of reducing CO₂ emissions below 1997 levels, but by 2015 rather than 2010 (Table 5.7). In 2010, CO₂ emissions are 17 percent (a full 100 MMT of C per year) below the business-as-usual case, but still 4 percent 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 percent for hybrid vehicles, and 15-20 percent 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 CO₂" 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 percent of the stock of locomotives by 2010 and 15 percent by 2015. In most cases, the majority of CO₂ emission reductions have yet to be realized, even by 2015. The point is not that little can be done to reduce transportation's CO₂ emissions. The point is that if CO₂ 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 is that fuel injection 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 penetrations follow an s-shaped curve that predicts 50 percent 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 5.7 to 5.9, 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 5.7 and 5.8. 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 5.9. 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 5.7 Market Penetration of Advanced Engines Domestic Passenger Cars - Efficiency Scenario

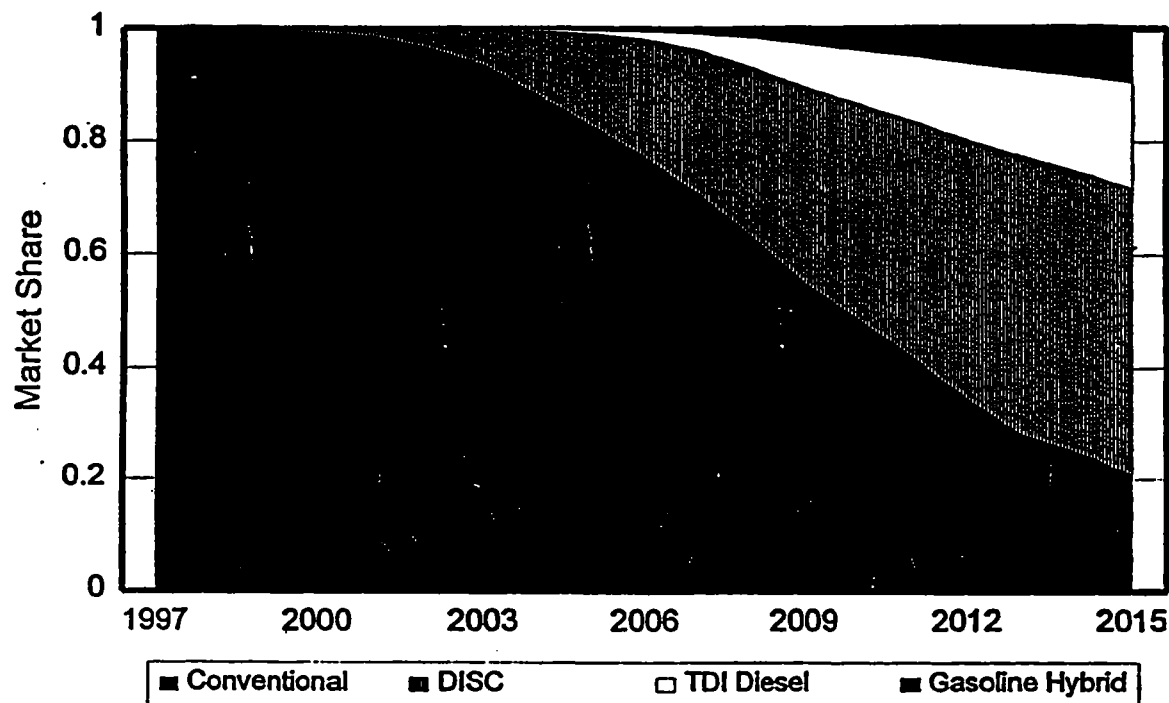


Figure 5.8 Market Penetration of Advanced Engines Domestic Light Trucks - Efficiency Scenario

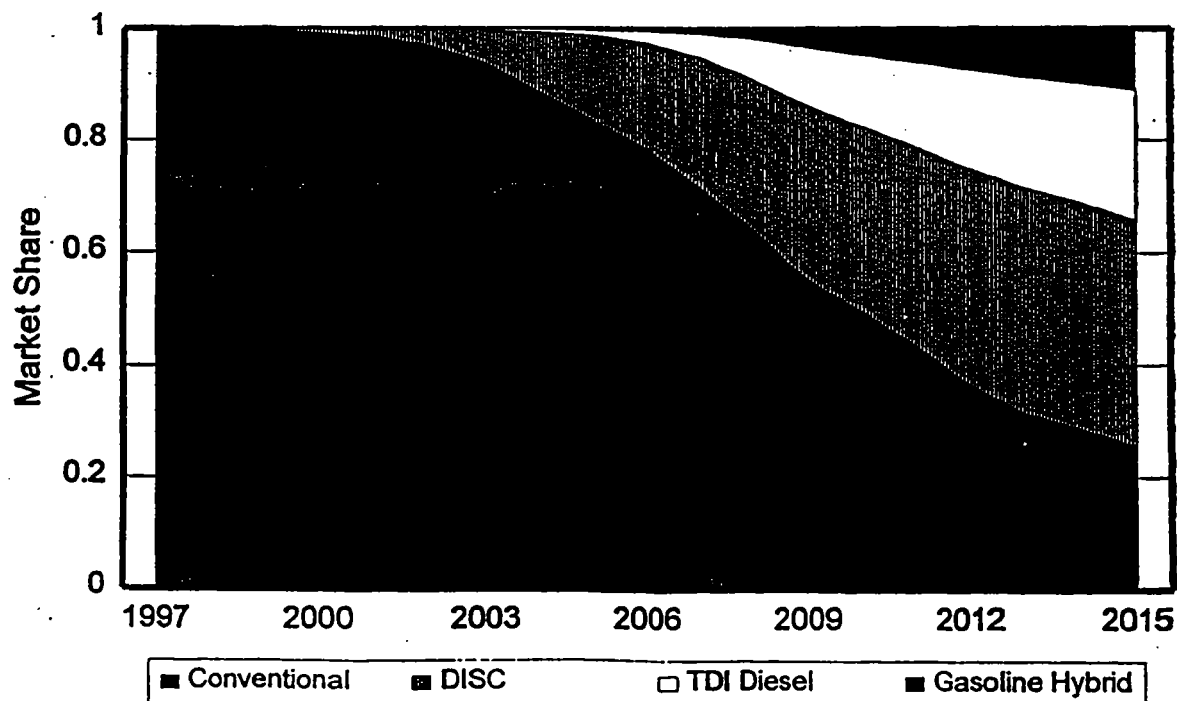
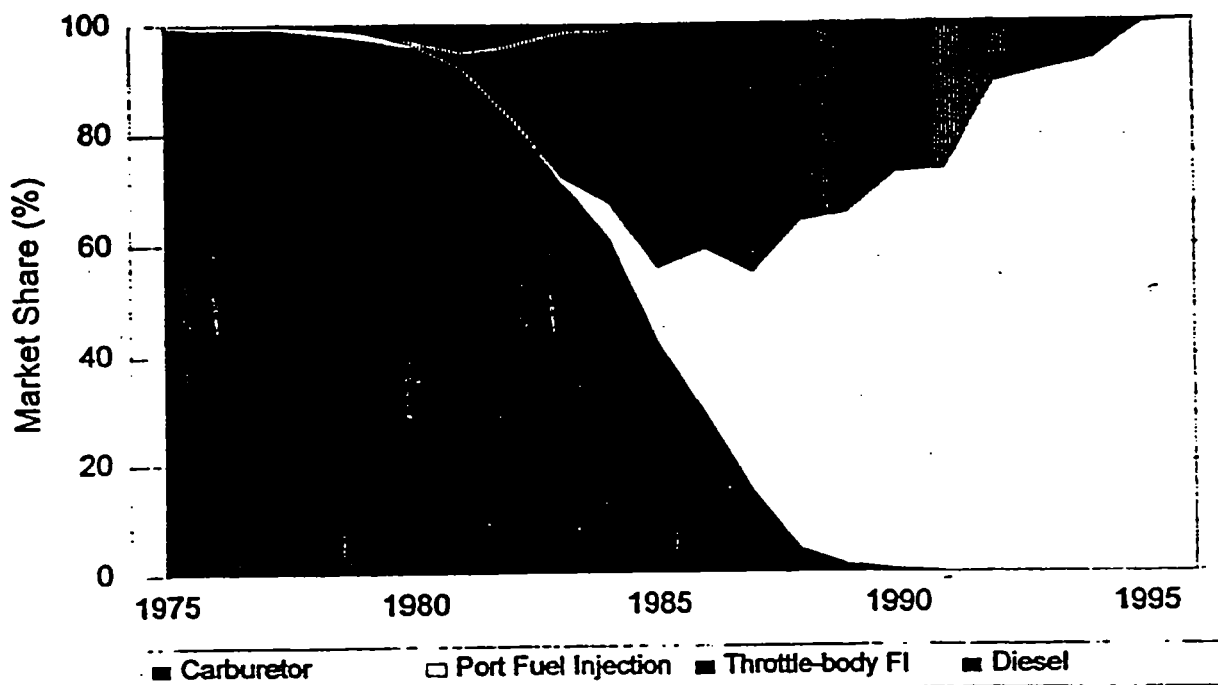


Figure 5.9 Penetration of Fuel Injection Technology



Source: Heavenrich and Murrell, 1996, table E-1.

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. 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.

On the basis of the simple comparison of incremental vehicle costs versus the value of fuel savings to the consumer, fuel economy improvements in the efficiency scenarios appear to be cost effective or not, depending on the discount rate assumed. For example, in the Efficiency scenario, the value of passenger car fuel economy improvements almost exactly equals their total cost at a 7 percent per annum real discount rate, but falls far short at a 20 percent annual rate. For light trucks, fuel savings easily exceed costs at 7 percent and 10 percent, but not at 20 percent. In the High Efficiency scenario, assumed technological breakthroughs permit higher fuel economy at very little increase in cost over the Efficiency scenario. As a result, savings exceed costs for all discount rates shown, except 20 percent for passenger cars.

Which is the correct discount rate is somewhat controversial. In the buildings chapter, for

example, a 7 percent real rate is used to value fuel savings. We believe the 20 percent rate should be used for valuing light-duty vehicle fuel economy savings for the following reasons. First, when consumers invest in a fuel economy technology, they are investing in a depreciating asset. Motor vehicles depreciate in real value by about 10 percent per year. Thus, a passenger car that cost \$20,000 when new, would bring a little more than \$12,000 five years later. We believe that it is reasonable to assume that incremental investments in fuel economy technology will depreciate at the same rate. Second, empirical evidence shows that vehicle use decreases with vehicle age at approximately 4 percent per year (Davis and McFarlin, 1996, table 3.11). By reducing the quantity of fuel consumed, this effectively reduces the value of future fuel savings at the rate of about 4 percent per year. Finally, consumers will have a simple discount rate, reflecting their time preference for money. If we assume that is 6 percent per year, we obtain a total discount rate of 10 percent + 6 percent + 4 percent = 20 percent. We recommend using that rate to value future fuel savings from the consumers' perspective. That rate is also consistent with the valuation of future fuel savings in the NEMS model. We show the lower rates here for purposes of comparison with other sectors.

Table 5.9. Simple, Total Cost-Effectiveness Estimates for Light-Duty Vehicle Fuel Economy Technology

Scenario	MPG	Incremental Cost	Passenger Cars		
			Value of Fuel Savings to Consumer		
			7% Real	10% Real	20% Real
Business as Usual	27.5	\$0	--	--	--
Efficiency	37.5	\$1,950	\$1,900	\$1,600	\$1,000
High Efficiency	43.1	\$2,000	\$2,550	\$2,150	\$1,350
			Light Trucks		
			7% Real	10% Real	20% Real
			7% Real	10% Real	20% Real
			7% Real	10% Real	20% Real
Business as Usual	20.5	\$0	--	--	--
Efficiency	27.1	\$1,500	\$2,300	\$1,950	\$1,200
High Efficiency	30.8	\$1,650	\$3,200	\$2,700	\$1,700

Gasoline prices assumed to remain constant at \$1.20 per gallon. Vehicle usage rate of 15,500 miles per year and lifetime of 14 years. MPG estimates discounted by 15% to reflect actual operating conditions.

Given our preferred method of valuing fuel savings, it would appear that the model is allowing a substantial amount of technological change that is not, on the basis of fuel savings, cost-effective to the average consumer. However, the NEMS model's fuel economy technology simulation also takes into account the fact that (1) the technology will presumably offer other benefits (e.g., lower emissions, better performance, etc.), and (2) not all consumers are identical (some will have lower discount rates and place a higher value on fuel economy, some will drive many more annual miles than average).

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. 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.

5.4 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 the 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 vehicle in 2020, assuming the necessary breakthroughs in a number of areas (e.g., manufacturing processes for composite materials, 2 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 accessories and low-energy-use design (e.g., advanced window coatings and insulation).

The current PNGV program is addressing many of the R&D roadblocks remaining, 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 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 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

¹³Actually, 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 that much more onerous.

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 emission diesel cycle engine (thermal efficiency of at least 55 percent 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 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 percent 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 technology 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 feedstocks 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 percent in 2010 and by almost 20 percent in 2015, relative to the "business-

¹⁴The 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.

¹⁵This technology is required for direct-injection gasoline engines as well.

as-usual" case. If important breakthroughs can be achieved in fuel cells and other key technology, 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 metric tons of carbon, increase from 487 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 percent 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 MMT 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 MMT, and reduces 2015 emissions to 484 MMT, just slightly below the 1997 level.

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 percent 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- CO₂ technologies. Second, the 1997 AEO 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- CO₂ 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.

Technology indeed 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- CO₂ technologies and a commitment to implement policies that will insure their adoption in the market.

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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 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 that year. 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. These changing dynamics of capacity expansion and system operation mean that one cannot assume that the average and marginal carbon intensities of electricity use (tons 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 the electricity sector ORCED projections with those developed by EIA in its *Annual Energy Outlook 1997* (AEO '97). We then develop a competitive-electricity market case for 2010. This is then 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. Utilities are required to offer transmission services to other parties under the same prices, terms, and conditions that the utility uses its system for its own purposes. 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 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 planned, built, and operated power plants to minimize the lifecycle 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.
- 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 generating capacity available 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 onpeak season and a second time for an offpeak season (Figure 6.1). We define the onpeak season as June through August, and the offpeak 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.

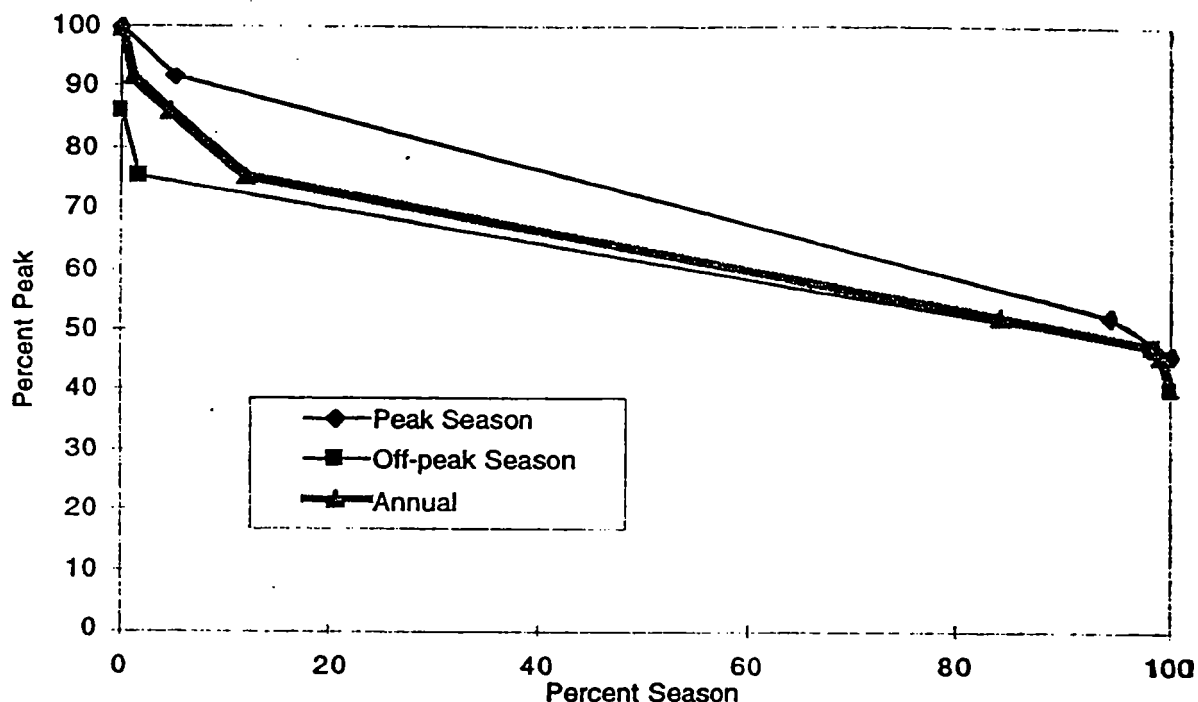
A load-duration curve is created by ordering demand (in MW) in terms of magnitude from highest to lowest. The resultant curve shows the percentage of time that demand exceeds a particular value, ranging from the one-hour peak demand down to the minimum demand.

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 offpeak 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 26th 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 offpeak 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.² 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 former elasticity adjusts the entire load duration curve up or down in response to decreases or increases in the average price of electricity. The latter 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.

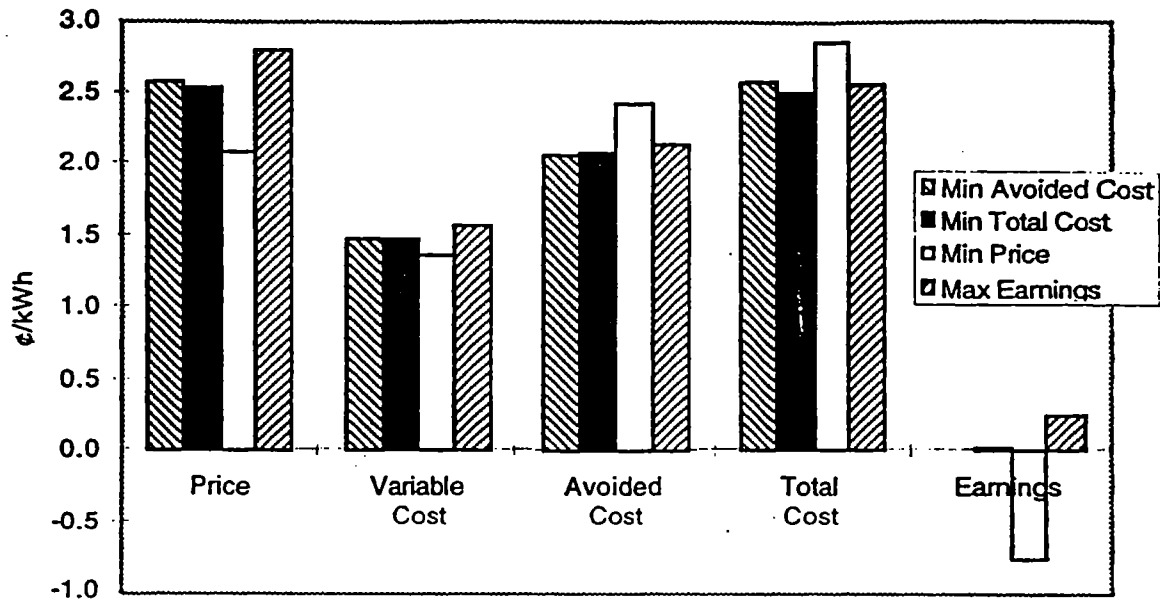
In addition to dispatching power plants and computing production costs, the model can also "optimize" the mix of generating units available for the year of analysis. (That is, the model includes a capacity-expansion module as well as a production-costing module.) We put optimize in quotes because the 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. As examples, the model could choose from among the following optimization functions:

- minimize total costs;
- minimize avoidable (fuel, variable and fixed O&M) costs;
- 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. Because this choice was conceptually the most appealing and the results the most reasonable for a system-wide optimization.

In addition to specifying the optimization function, the user can also specify constraints on individual generating units or the mix as a whole. As examples, these constraints 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). Constraints can be specified for a minimum capacity reserve margin, for a maximum carbon emission allowance, to ensure that each generating unit recovers at least its variable plus avoidable fixed costs, and so on.

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 AEO '97

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, such as 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.³ 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. Thus, the regulations proposed by the Environmental Protection Agency 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 year 2010 base case 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 AEO '97, 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 AEO '97 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 estimates of the following costs 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:⁴

Fuel	1.35
Variable O&M	0.18
Fixed O&M	0.51
<u>Capital</u>	<u>1.00</u>
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, A&G, and customer service from EIA's total capital cost:

$$[2.32 - (0.52 + 1.46) \cdot 0.63 - 0.08] = 1.00 \text{¢/kWh.}$$

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:⁵

$$(0.98 + 0.67 \cdot 0.88) = 1.57 \text{¢/kWh.}$$

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 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 AEO '97	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 AEO '97 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 AEO '97 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 EIA's AEO '97 year 2010 values, 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 offpeak). The new system load has a peak demand that is 3.4% below the AEO '97 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 AEO '97 base case, carbon emissions are lower. This situation is a consequence of the reduction in coal use and the increase in 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." Because of this, 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.

**Table 6.3 Comparison of Year 2010 Forecasts:
EIA AEO '97 and the ORCED Base Case for a Competitive Electricity Industry**

	EIA AEO '97	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, million metric tons	631	625

Overall, ORCED prices under restructuring did not differ greatly from the AEO '97 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 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 avoided 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 AEO '97, (less than 5% different when factoring in transmission and distribution prices) we simply used the AEO '97 price forecasts for analysis of energy efficiency savings in the other chapters of this report.

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 operating & maintenance 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 metric ton of carbon, to be consistent with the rationale used in the demand-side efficiency scenarios.

Once power plant production levels were determined, the amount of carbon and primary energy used 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 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.

Figure 6.3 Carbon Production versus End-Use Demand:
Reductions due to Energy Efficiency and Carbon Management

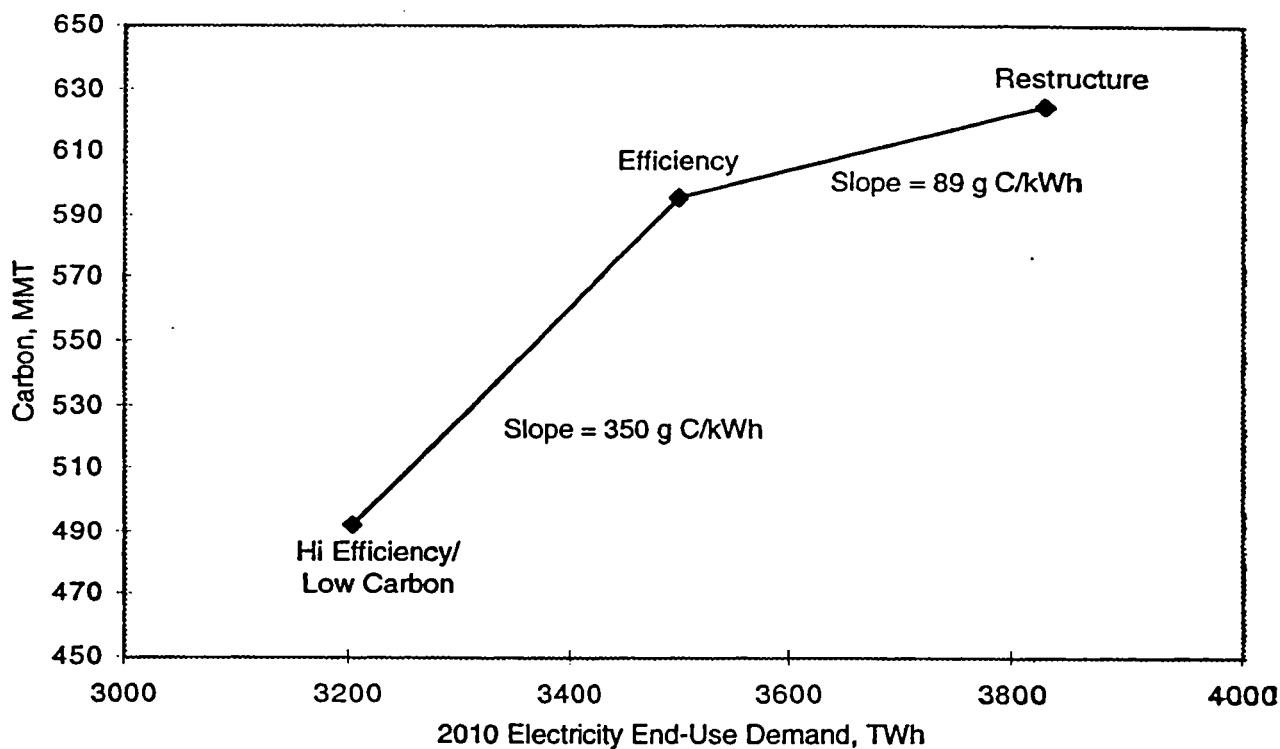


**Figure 6.4 Primary Energy Production versus End-Use Demand:
Reductions due to Energy Efficiency and Carbon Management**

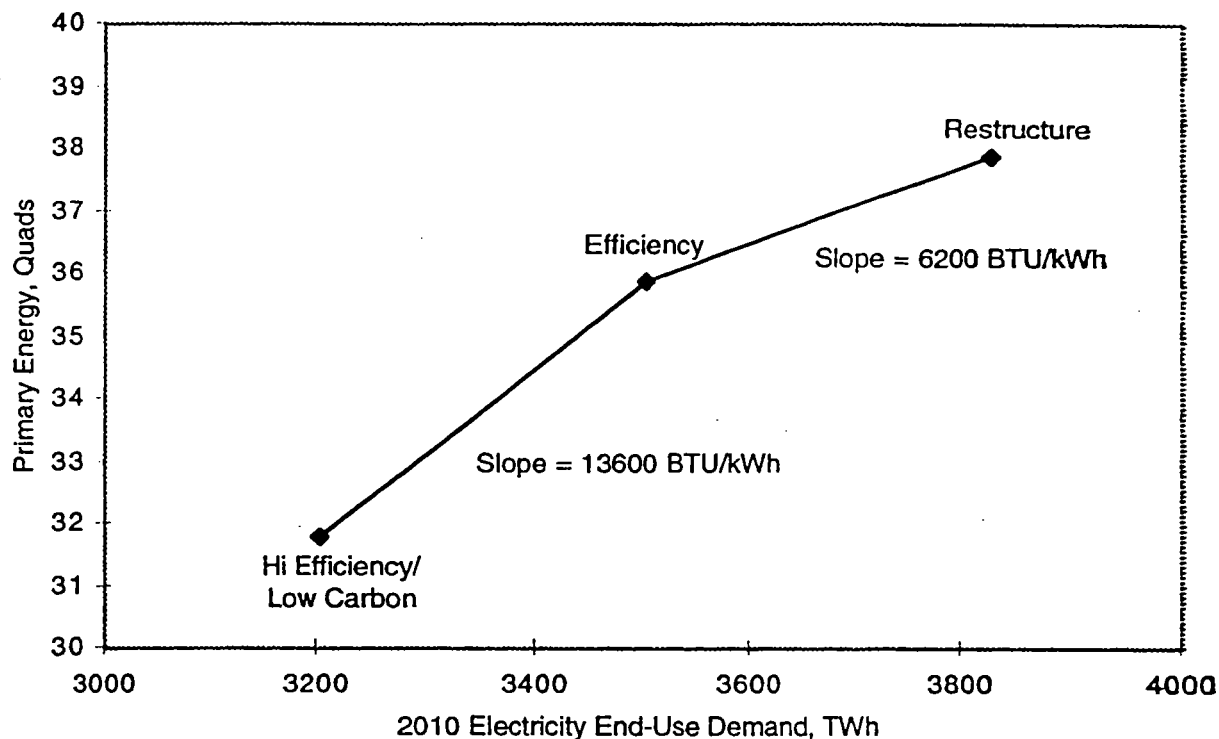


Table 6.4 summarizes the results for the three scenarios. Table 6.5 describes these results in terms of percent change relative to the base case for a competitive utility industry. The "efficiency" case yielded a 8.5% reduction in electricity end-use demand and the "high efficiency/low carbon" case cut electricity use by 16.3% relative to the restructuring case summarized in Table 6.3.

**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, million metric tons	625	596	492
Average carbon emissions, kg/MWh	163	170	154
Marginal carbon saved, kg/MWh		89	350

The Efficiency scenario had a lower percentage reduction in carbon (4.6%) than in end-use energy (8.5%) (Figure 6.5). The difference occurred 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.) Capacity and generation dropped for combined-cycle units by about 27%. Capacity for combustion turbines dropped 28%; generation dropped by 68%. Coal and gas-powered steam plants actually increased their production slightly.

On the other hand, the High Efficiency/Low Carbon case had 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 metric ton of carbon changed the mix of technologies used to produce electricity. Over 16% of the coal capacity was retired, and the remaining, more-efficient coal plants operated at a lower capacity factor. Over-all, generation from coal declined 18% from the reference case. Capacity from combined cycle plants actually increased over the amount in the Efficiency case, but still had an 14% decline from the reference case. Combustion turbine generation declined 84% from the reference case while combined cycle generation declined only 13%.

**Table 6.5 Comparison of Year 2010 Forecasts:
Effects of "Efficiency" and "High Efficiency/Low Carbon" Scenarios**

	Percent 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	-0.2
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%

Generating prices and costs stayed about the same under the efficiency scenario. In the high efficiency/low carbon scenario, prices and costs increased around two-thirds of a cent because of the additional charge of \$50/metric ton 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%, this only represents 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%.

Since 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/metric ton 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 per ton saved of \$30.

Allocating the carbon savings between the buildings and industrial sectors, we find that in the Efficiency case the buildings sector (residential and commercial) saved 19.4 million metric tons

of carbon. The industrial sector saved 9.6 million metric tons (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, in Million Metric Tons

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

Some of the 133 million metric tons 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 were caused by the change in electricity generation mix that resulted from the charge of \$50/metric ton of carbon. Two methods of allocating the carbon savings between the end-use and supply sectors were examined.

- In the first method, ORCED modelled the high efficiency/low carbon case without the \$50/metric ton charge in the supply sector. The result was a savings of 56 million metric tons of carbon. The rest of the carbon savings (77 million metric tons) is attributed to the electricity sector.
- In the second method, the average carbon per kWh as forecasted by AEO for the year 2010 was used to calculate the carbon displaced by the 630 TWh of reduced electricity demand. This method allocated 103 million metric tons of carbon savings to the end-use sectors and 30 million metric tons to the electricity sector.

The results of these alternative allocations (including the distribution of carbon savings across the buildings and industrial sectors) are shown in Table 6.7. The total carbon that is displaced by the lower electricity demand is the same (133 million metric tons), but the allocation between the end-use and supply sectors varies widely depending on the method used to allocate the savings.

Figure 6.5 Energy and Carbon Changes from Restructure Case

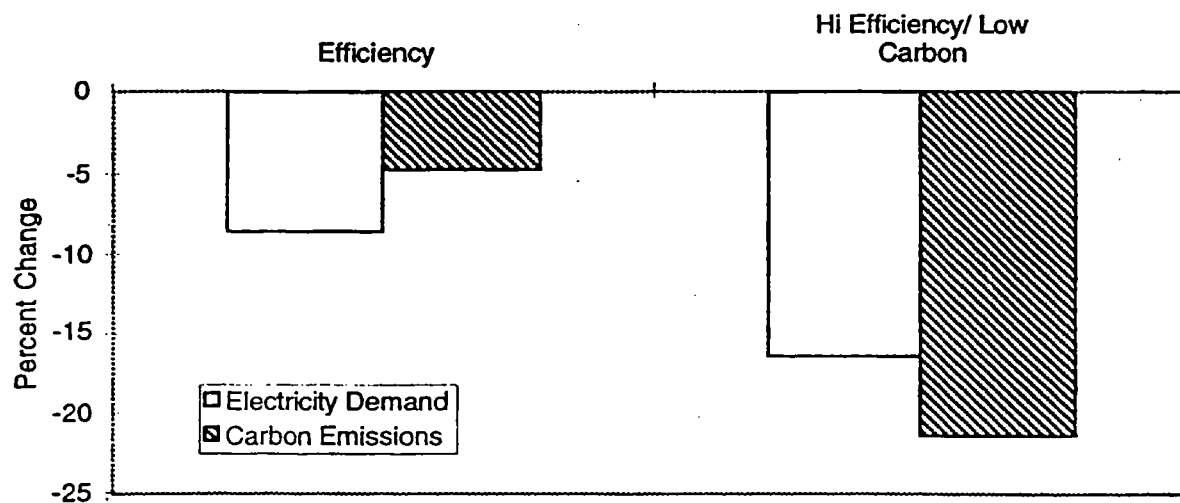


Figure 6.6 Generation by Technology Under Each Scenario

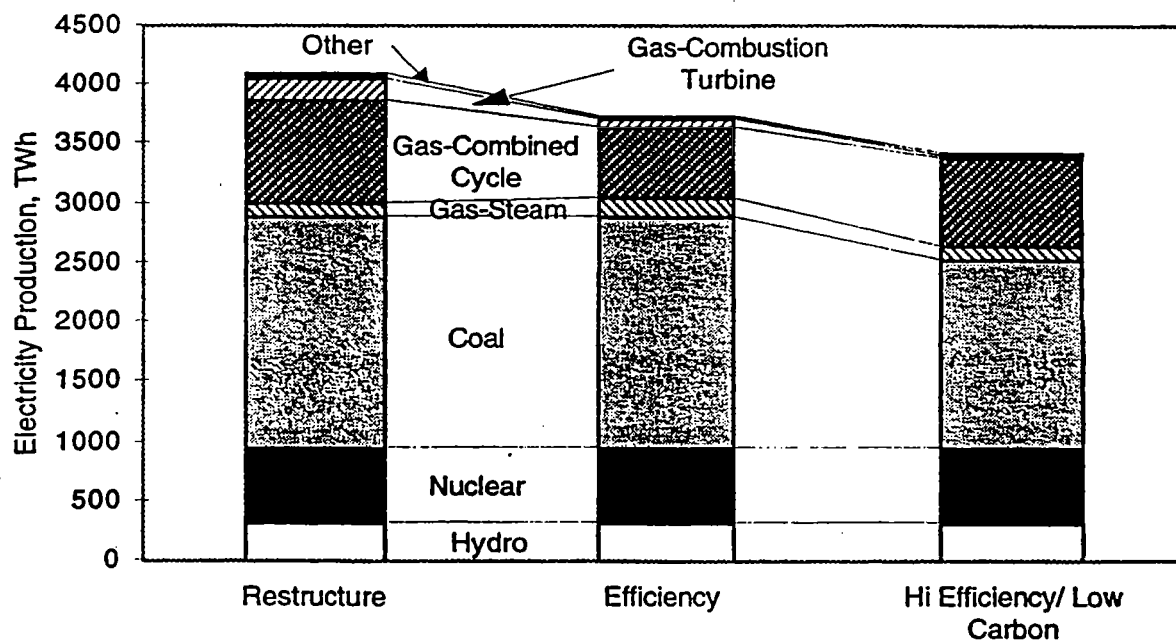


Table 6.7 Allocation of Carbon Reductions from the Electricity Saved by the High Efficiency/Low Carbon Case, in Million Metric Tons

Sector	Method 1: Carbon Reduced by End-Use Sector	Method 1: Carbon Reduced by Electricity Sector	Method 2: Carbon Reduced by End-Use Sector	Method 2: Carbon Reduced by Electricity Sector	Total
Buildings (Residential)	21	--	38	--	21 - 38
Buildings (Commercial)	16	--	30	--	16 - 30
Industry	19	--	35	--	19 - 35
Subtotal					56 - 103
Electricity Sector	--	77	--	30	30 - 77
Total	56	77	103	30	133

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 the EIA AEO '97 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 intended to reflect the ways in which a fully competitive industry might operate. Compared to the AEO '97, 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 developed by LBNL and ANL. The "efficiency" case cut electricity use by 8.5%, which led to a 4.6% reduction in carbon emissions. The "high efficiency/low carbon" case cut electricity use by 16.3%, which led to a 21.2% reduction in carbon emissions.

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¹ States will continue to oversee power-plant siting and environmental emissions.

² 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.

³ Inclusion or exclusion of the data for cogenerators (which account for about 4% of electricity in the year 2010) is another source of confusion.

⁴ According to the EIA AEO '97, total generation in 1995 was 3246 billion kWh and sales totaled 3008 billion kWh, implying a loss of 7.3%.

⁵ This 88% is derived from ORCED's estimates of fuel and O&M costs $[=1.35/(1.35+0.18)]$.