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

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

3.3 SCENARIOS FOR THE YEAR 2010

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

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

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

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

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

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

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

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

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

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

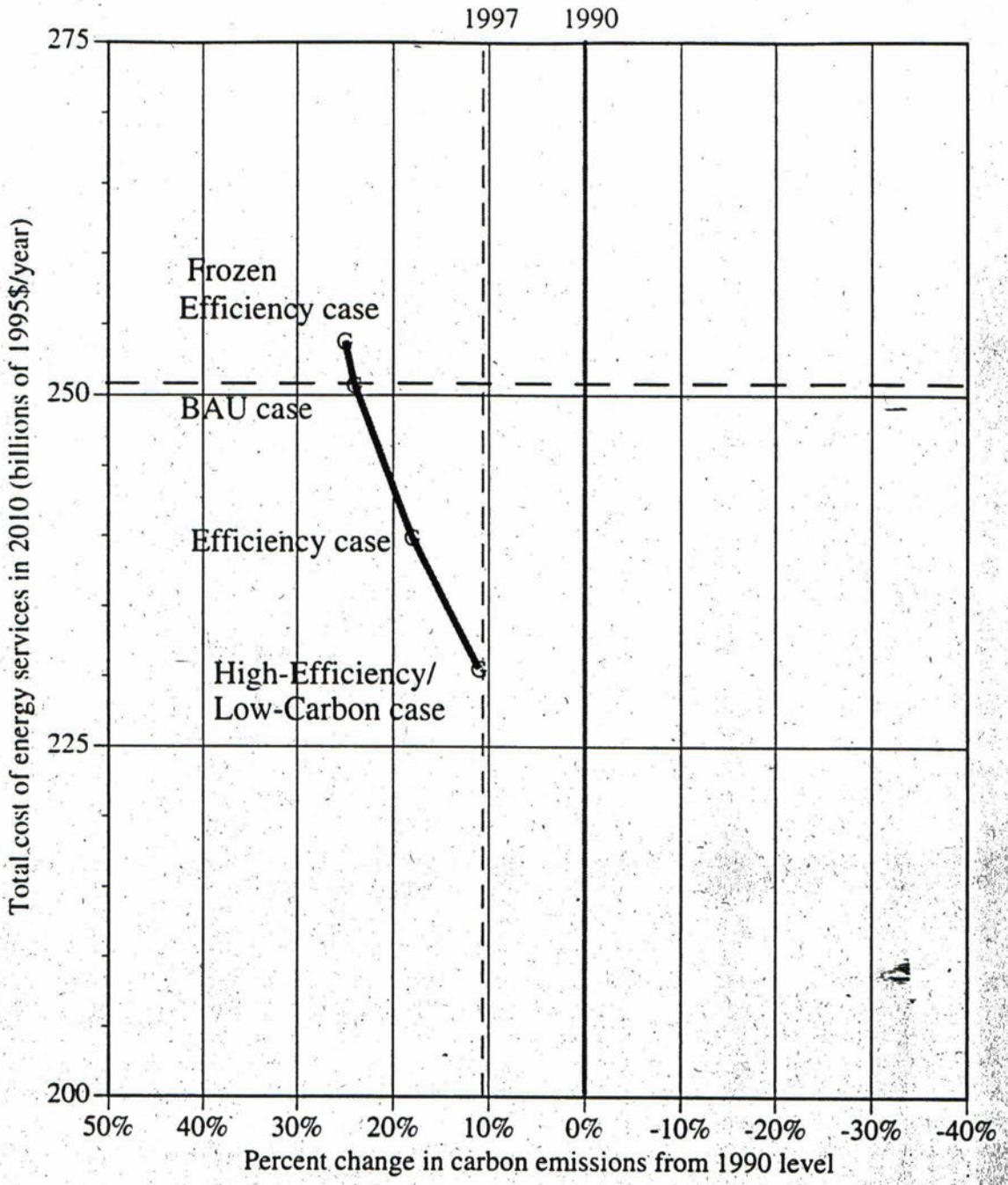
Note: Table does not include effects of building-sector fuel cells. Numbers may not add to the totals due to rounding.

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

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

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

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



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

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

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

3.3.1 Business-as-Usual Scenario

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

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

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

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

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

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

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

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

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

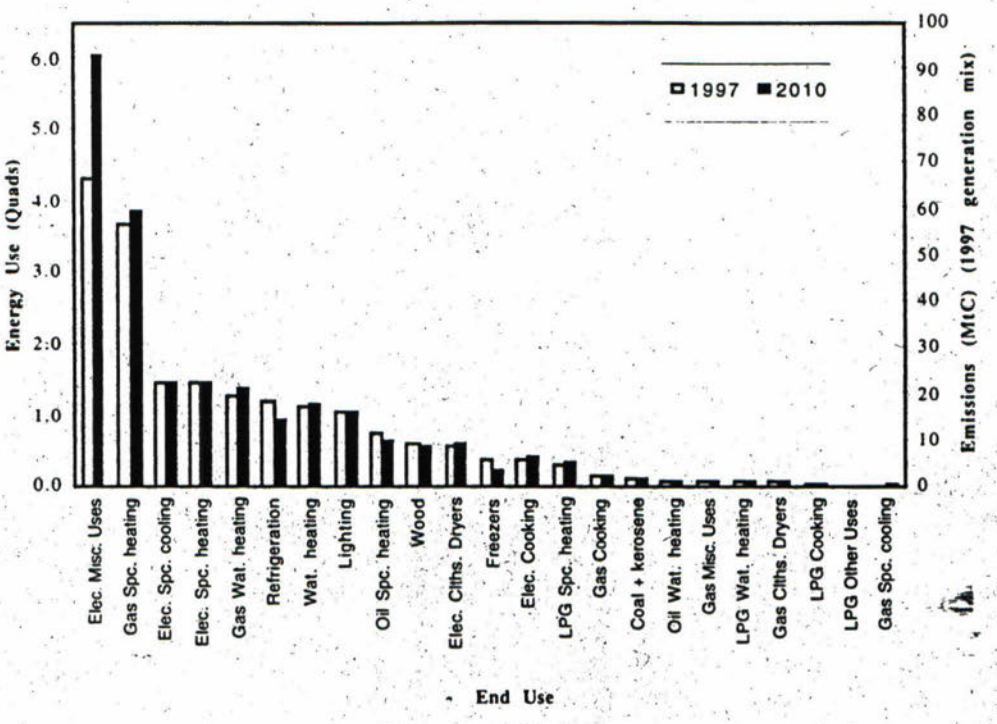
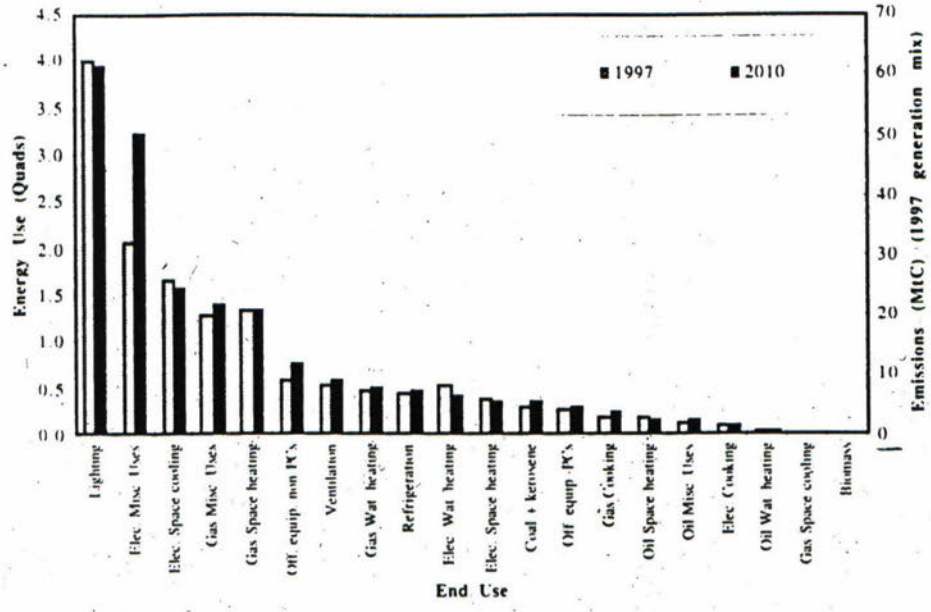


Figure 3.3 Commercial Sector Primary Energy Use and Carbon Emissions in 1997 and 2010 by End-Use for the Business-As-Usual Scenario



3.3.2 Maximum Cost-Effective Energy-Efficiency Potential

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

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

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

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

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

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

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

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

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

Figure 3.4 End-Use Electricity Savings, 2010

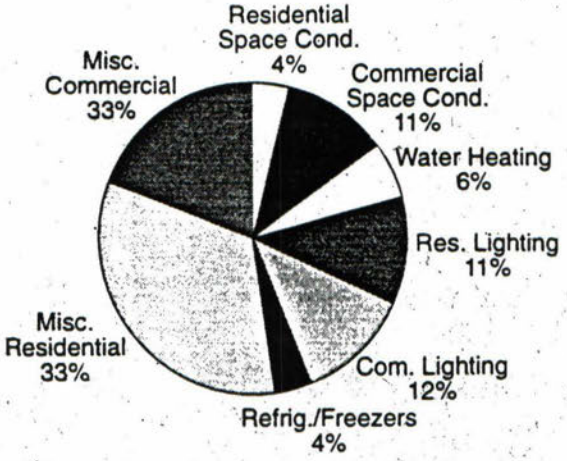
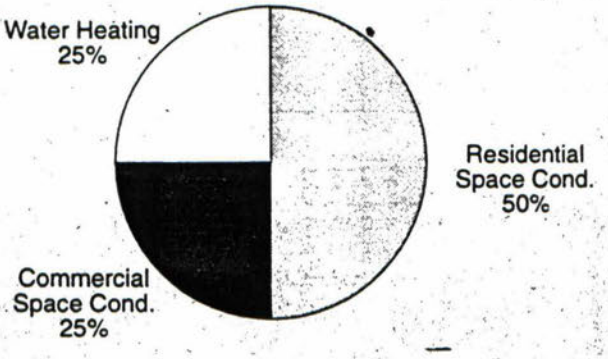


Figure 3.5 End-Use Natural Gas Savings, 2010



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

3.3.3 Efficiency Scenario Results

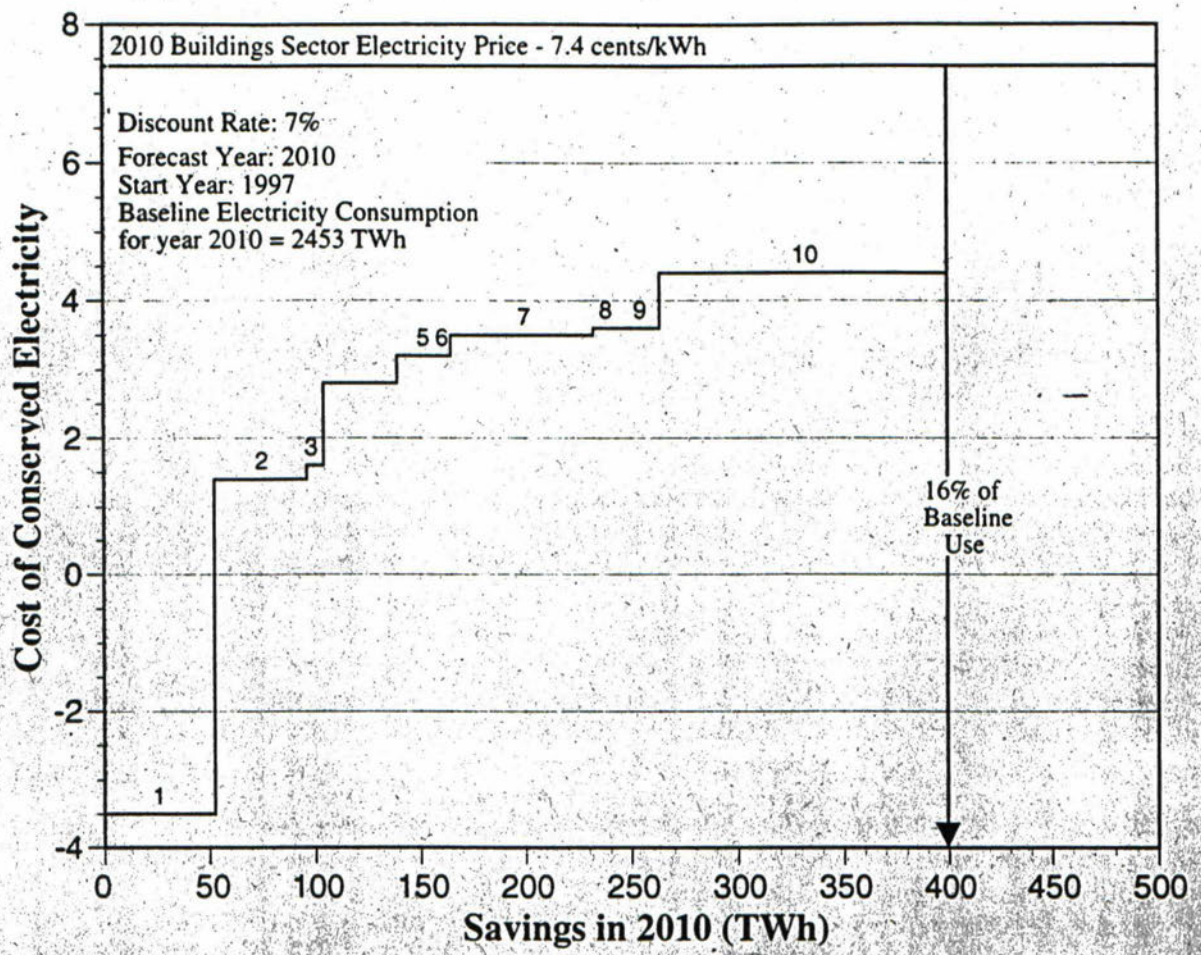
The efficiency scenario assumes that 35% of the maximum cost-effective efficiency savings are achieved by 2010. This assumption is based on expected savings resulting from a moderately vigorous effort to reduce energy use and carbon emissions using a combination of policy mechanisms that may include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

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

3.3.4 High-Efficiency/Low-Carbon Scenario Results

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

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



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

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

Improving Efficiency and Saving Capital

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

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

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

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

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

3.4 POTENTIAL FOR ADVANCED TECHNOLOGIES IN 2020[6]

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

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

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

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

3.4.1 New Technologies and Practices

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

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

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

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

3.4.1.1 Advanced Construction Methods and Materials

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

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

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

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

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

3.4.1.2 Environmental Integration and Adaptive Envelopes

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

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

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

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

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

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

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

Mitigating Urban Heat Islands With Cool Roofs And Trees

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

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

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

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

3.4.1.3 Multi-Functional Equipment and Integrated System Design

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

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

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

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

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

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

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

3.4.1.4 Advanced Lighting Systems

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

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

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

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

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

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

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

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

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

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

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

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

3.4.1.5 Controls, Communications, and Measurement

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

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

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

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

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

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

3.4.1.6 Self-Powered Buildings

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

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

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

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

Potential Additional Savings From Advanced Fuel Cell Technologies

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

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

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

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

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

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

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

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

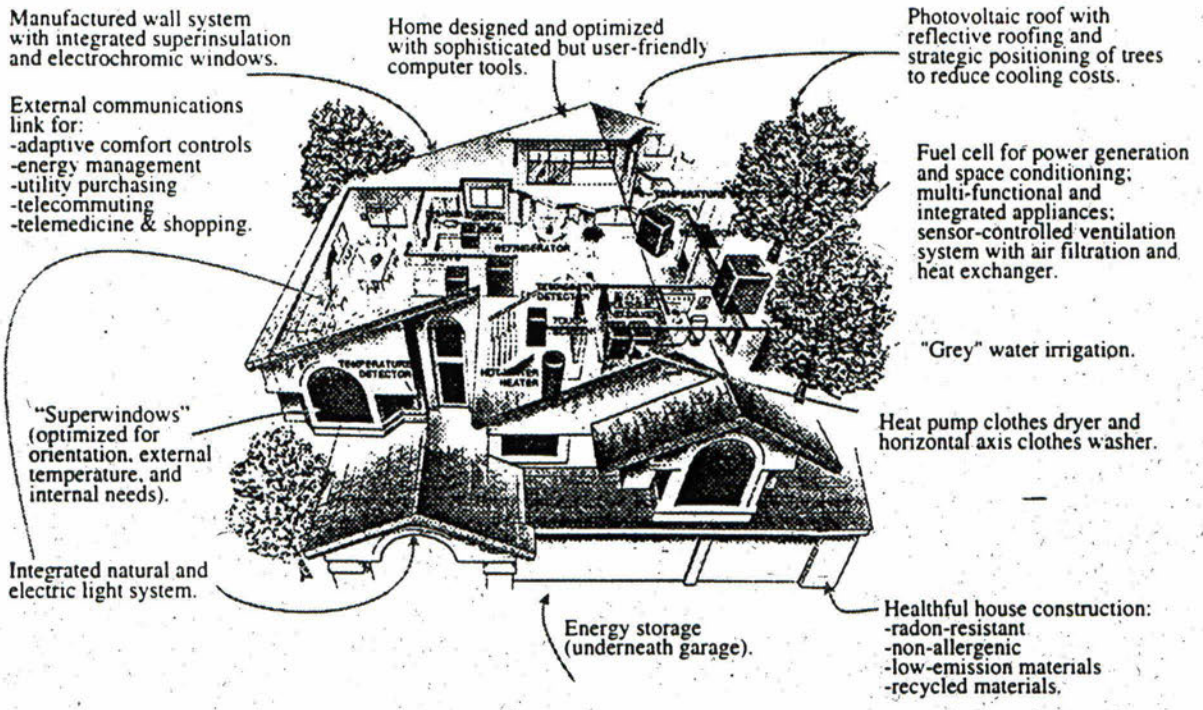
3.4.2 Best Practice Buildings in the Year 2020

3.4.2.1 "Best Practice" Housing in 2020

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

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

Figure 3.7 "Best Practice" Home of the Year 2020



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

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

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

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

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

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

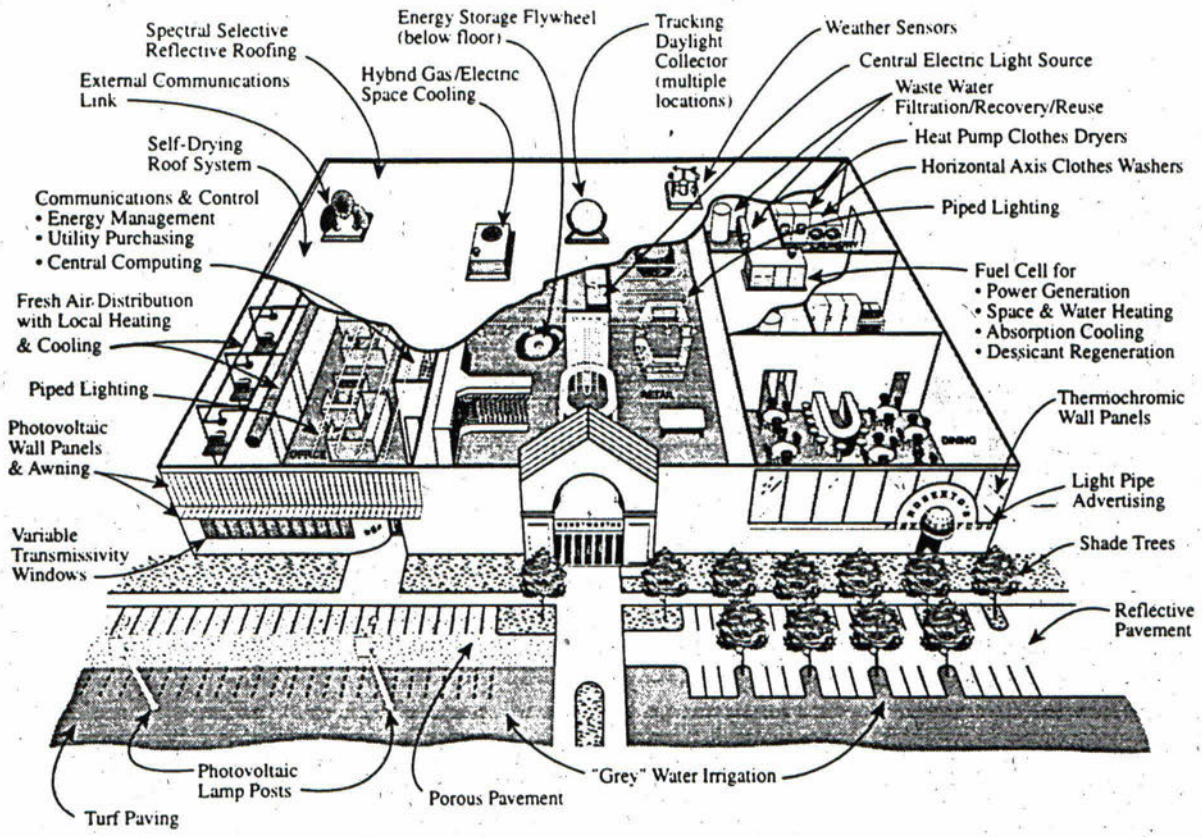
Home computers and sophisticated communication systems will begin to permit the use of the home as the location of office, secondary school, routine medical treatment, and selected shopping activities. This will begin to change the "mix" of building types as well as the need to commute to these activities.

3.4.2.2 "Best Practice" Commercial Buildings in 2020

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

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

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



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

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

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

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

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

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

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

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

3.5 IMPROVEMENTS TO THIS ANALYSIS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.6 SUMMARY AND CONCLUSIONS

Our analysis leads to the following key results for 2010:

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

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

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

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

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

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

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

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

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

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

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

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

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

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ENDNOTES

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

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

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

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

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

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

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

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

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

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

Chapter 4

THE INDUSTRIAL SECTOR

4.1 INTRODUCTION

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

4.1.1 Approach

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

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

4.1.1.1 Scenario Analysis

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

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

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

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

4.1.1.2 Technology Examples

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

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

Energy-Intensive Industries

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

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

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

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

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

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

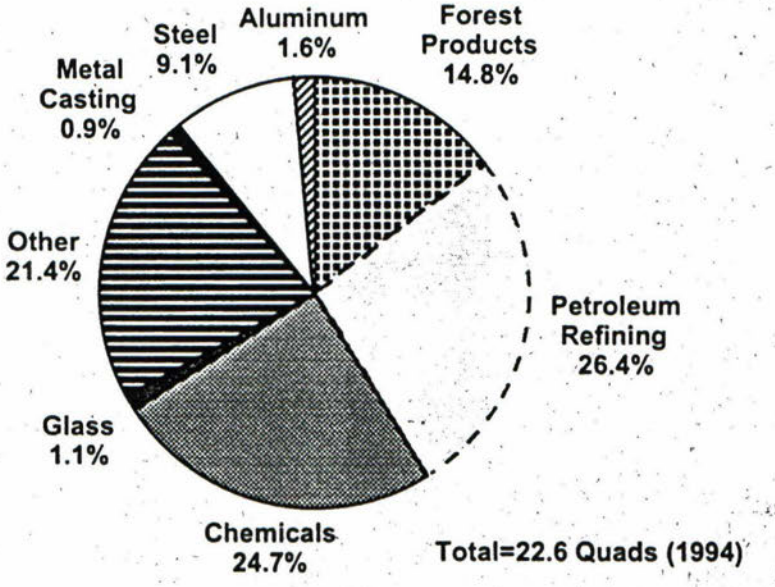
Stone, Clay and Glass Products. "Nonmetallic Mineral Products," under NAICS, includes cement, glass (a Vision Industry), bricks, lime, and other stone and ceramic products. Pyroprocessing, or the application of heat to assure a chemical reaction, is required in most of these subindustries, which is what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

4.1.1.3 A Continuing Stream of New Technologies

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

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

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



4.2 ENERGY EFFICIENCY EMISSIONS REDUCTIONS

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

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

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

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

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

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

Policies that might reduce these effects are:

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

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

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

4.2.1 Business-as-Usual Case

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

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

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

4.2.2 Efficiency and High-Efficiency/Low-Carbon Cases

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

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

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

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

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

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

* Expanded renewable use is considered in Section 4.3.

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

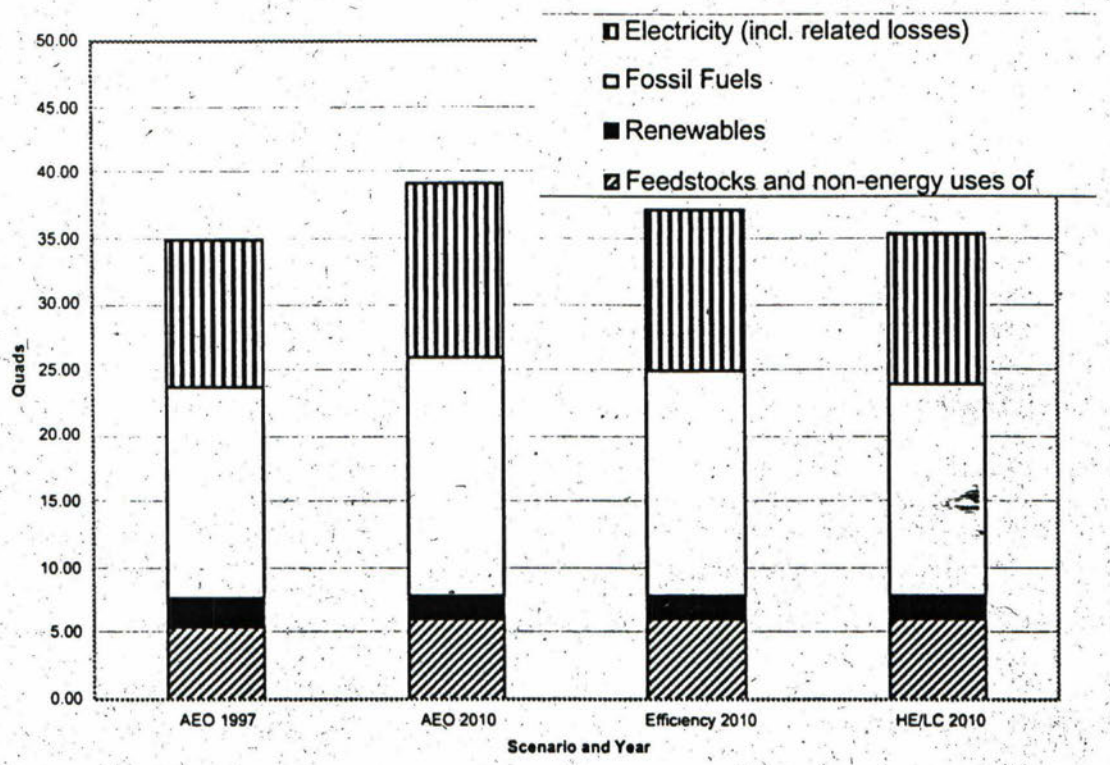


Table 4.2 shows the results of these analyses for ten major economic sectors of U.S. industry.[7] The results in Table 4.2 are expressed in terms of an additional annual percentage reduction in sectoral energy intensity compared with the BAU case. The efficiency case reduces total energy intensity growth by an additional 0.5% per year. The HE/LC case reduces the growth in energy intensity by over 1% per year, relative to the BAU case, and reduces the growth in electricity use by more than 1% annually (1.3%).

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

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

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

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

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

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

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

The difference between light and heavy manufacturing is a major source of the difference in the energy savings (on a percentage basis) between fossil fuels and electric energy. One should note that,

while these percentage savings vary, a significant portion of the energy savings in absolute terms still come from fossil fuel use reduction in heavy industry, e.g. fossil fuel reductions in heavy manufacturing is about 8% while the industry total for fossil fuels is about 12%.

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

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

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

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

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

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

Table 4.4 Change in Industrial Energy Use by Fuel Type

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

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

Table 4.5 Carbon Emissions Estimates (MtC per year)

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

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

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

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

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

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

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

4.2.3 Comparison with the NEMS model

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

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

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

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

4.2.4 The Historical Context of Energy Efficiency in Industry

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

technologies that are currently, or will soon be, available, the efficiency gains and energy and carbon savings projected could easily be achieved.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

The HE/LC case also focuses on 'cost-effective' investment under the same notion of these lowered, strategic, marginal rates of return. However, one important difference in the HE/LC scenario is that a higher adoption rate is assumed. While some additional penetration, relative to the BAU, may be accounted for by further transformation of the market of energy-efficient practices we feel that some accelerated retirement may also take place. When the economic losses of accelerated retirement are accounted for, this implies that, at the margin, all investments are not likely to be cost-effective at our

assumed 15% CRF. Since we do not have a model to account for this potential early retirement and the economic losses, we must caveat our estimates of investment. The energy savings from the HE/LC scenario in Table 4.9 does not change, but the investment cost may be understated by the amount of loss due to any early retirement that may occur. Because the net benefit is still greater than the annualized investment we calculate, then unaccounted costs may be about twice our estimated energy-efficiency investment, with the HE/LC scenario remaining 'cost-effective' on average.

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

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

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

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

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

4.3 ADDITIONAL EMISSIONS REDUCTIONS FROM INDUSTRIAL LOW-CARBON TECHNOLOGIES

4.3.1 Introduction and Summary

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

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

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

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

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

In the following sections, we provide examples of the three types of low-carbon industrial technologies. The Advanced Turbine System (ATS) described in Section 4.3.2 is an example of a PSEM technology. It is a combined heat and power (CHP) system that replaces grid electricity and steam from industrial boilers with a highly efficient on-site natural gas-fired turbine that generates both electricity and steam. The carbon reductions from on-site CHP were not included in Section 4.2.2. The ATS may also further maximize system efficiency by replacing electricity used to drive motors that drive equipment with direct power for the equipment. Even when used as a power-only technology, ATS reduces carbon emissions because it is located on-site – avoiding transmission and distribution (T&D) losses. The ATS is also a fuel-switching technology if it replaces high-carbon fuels such as coal used in the boilers with natural gas or no-carbon biomass gas.

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

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

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

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

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

*These reductions are not accounted for in Section 4.2.2.

4.3.2 Power System Efficiency Maximization Technologies

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

4.3.2.1 Advanced Turbine Systems (ATS) for Industrial Applications

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

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

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

This "new steam" market explains much of the additional penetration of the ATS into traditional cogeneration and power-only markets. The market involves, for example, sites that operate one process shift using the ATS in CHP mode (possibly buying additional electricity from the grid) and another shift where the ATS simply generates electricity for site use and possibly for nearby electrical customers. The ATS may also generate excess steam that it uses for electricity generation. The ATS may also generate steam and electricity for sale.

Considering the large markets not yet served by this type of CHP, industry experts predict that the availability of advanced turbines will double the growth rate of new CHP capacity (Carroll 1997). This growth will greatly exceed the historic industrial market penetration of cogeneration,[12] particularly for smaller power technologies used to meet internal energy requirements. Under the efficiency or high-efficiency/low-carbon scenarios, the change in the market will occur even faster. Relatively higher prices for carbon-based fuels will encourage dispatching of electricity from low-carbon fuels, reform of environmental permitting, and utility regulations and will thus accelerate the replacement of boilers by on-site ATS cogeneration. The turbine's low installed costs, low NO_x emissions, and ability to generate electricity when steam is not needed will also contribute to the rapid growth of this new steam market.[13,14]

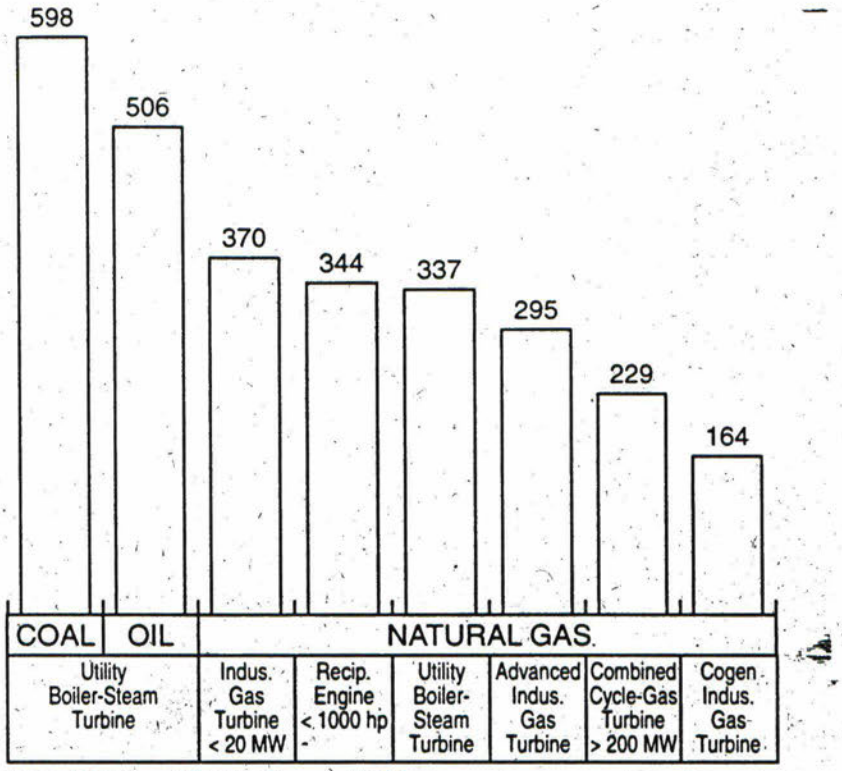
This "new steam" market is an entirely new type of market not considered in most energy forecasting models. It is new CHP capacity in which power and heat are not balanced and where the desire to generate electricity is more important than getting the perfect steam match. Unlike traditional cogeneration equipment that is optimized for a particular E/T ratio, ATS CHP systems run at high efficiency in a variety of steam and electricity configurations. This last feature means that the ATS can generate electricity continuously but steam only when needed. As detailed in Appendix D-3, this

market will spur creative uses of both heat and power. For analytic purposes, we have analyzed the "new steam" market as if it were two separate CHP and power-only markets. We decomposed new steam into traditional CHP (cogeneration assuming heat/power balance) and Power-Only (PO):

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

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

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



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

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

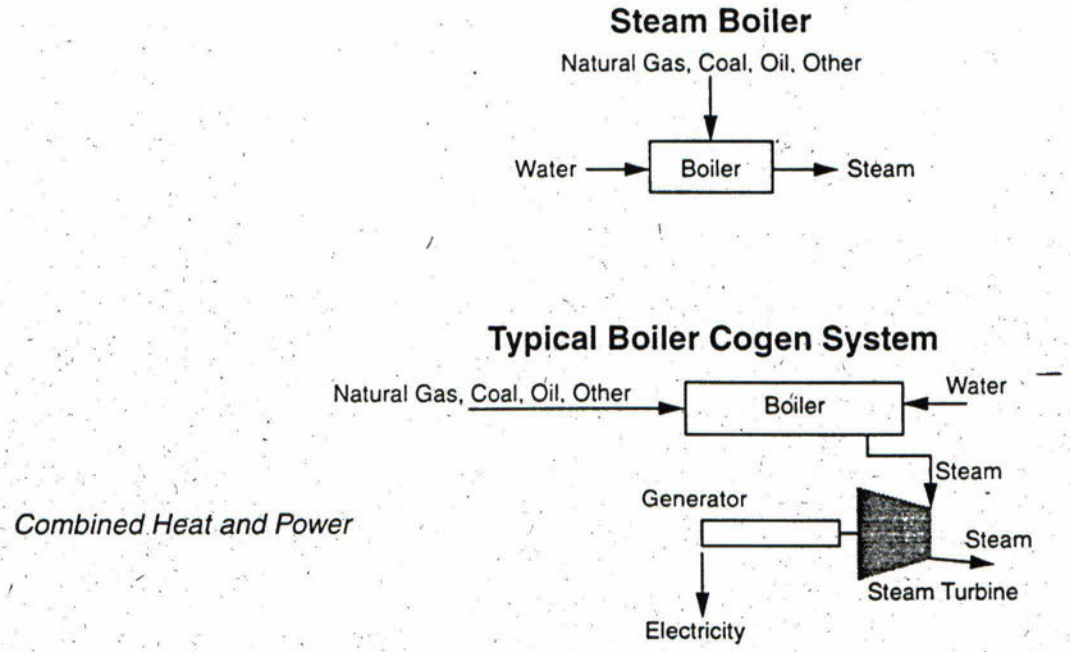


Table 4.12 shows the contributions of these two "markets" to the total carbon reductions. As described in Appendix D-3, the power-only carbon reductions are much smaller because we assume that the power being displaced is also quite efficient. Thus, the ATS can only take credit for carbon reductions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

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

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

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

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

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

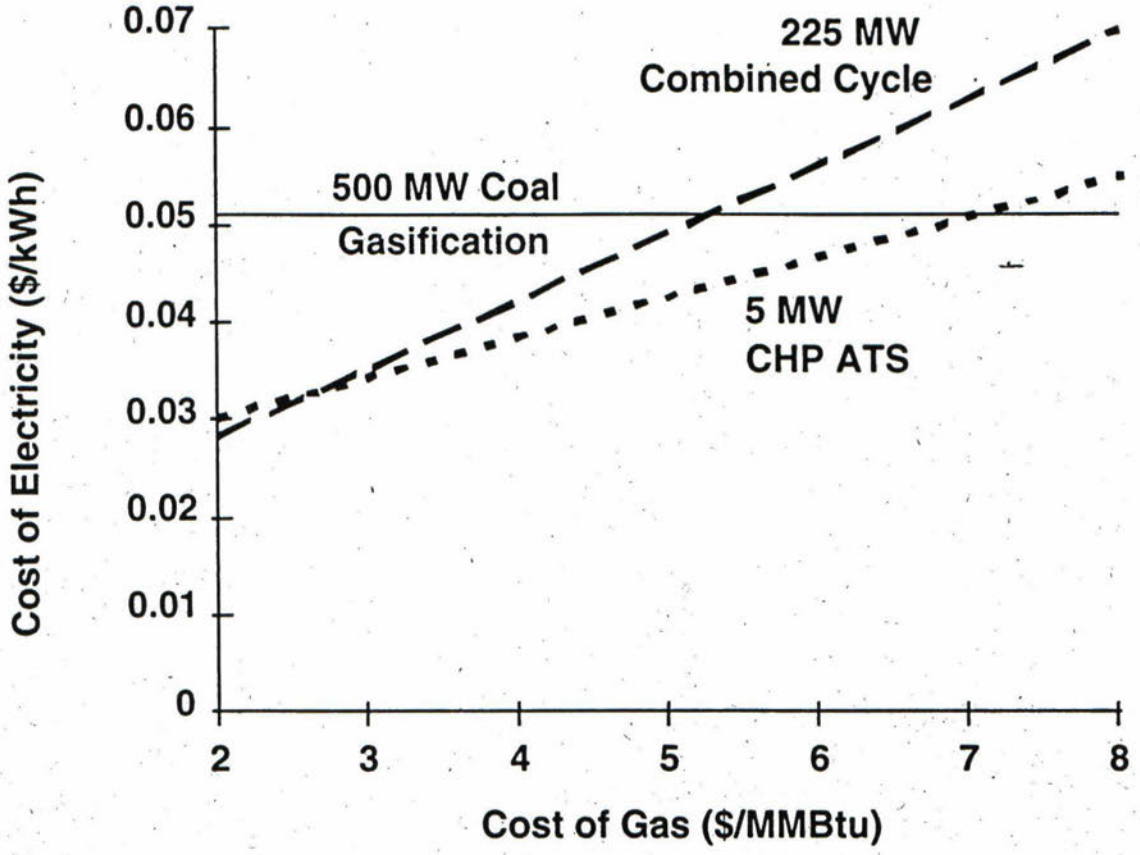
We estimate ATS carbon reductions of 5-7 MtC equivalent for the efficiency case (see Appendix D-3). This corresponds to an electric capacity of 23-27 GW and requires 0.5 TCF of additional natural gas (5% of 2010 BAU industrial demand) due to fuel switching from oil and coal biolers. For the high-efficiency/low-carbon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

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

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

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

Figure 4.5 Electric Generation Cost Comparison



Source: Onsite Energy (1994)

4.3.3 Fuel-Switching Technologies

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

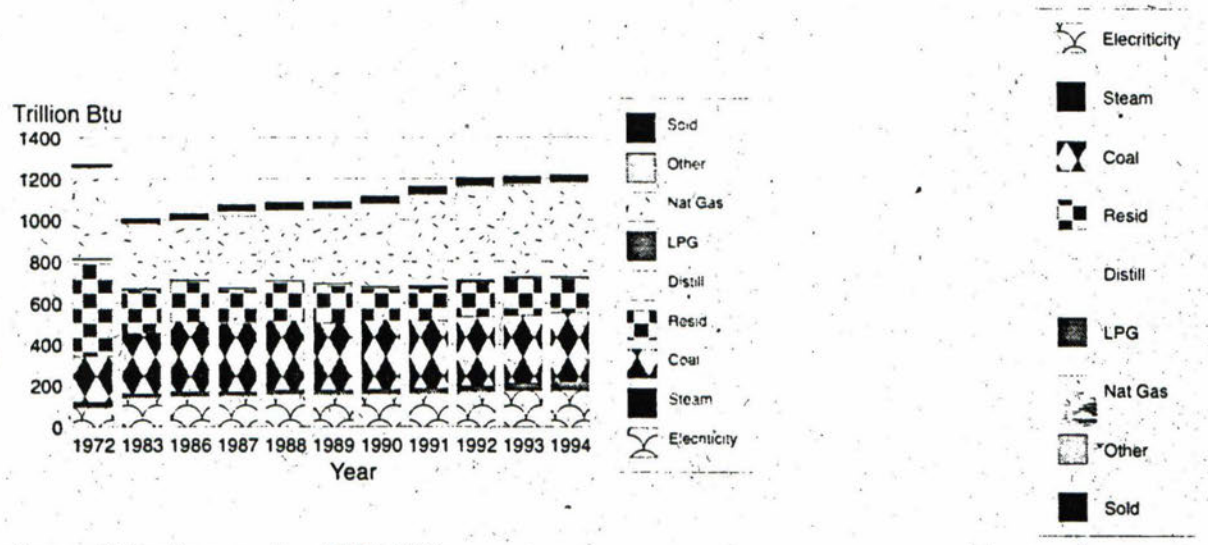
modeling calculations of Section 4.2.2 and is responsible for the carbon offsets calculated here. Although no examples are provided, other renewable energy-powered industrial technologies (e.g., solar detoxification) could also be considered low-carbon fuel-switching technologies.

4.3.3.1 Integrated Gasification Combined Cycle Technology for the Forest Products Industry

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

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

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



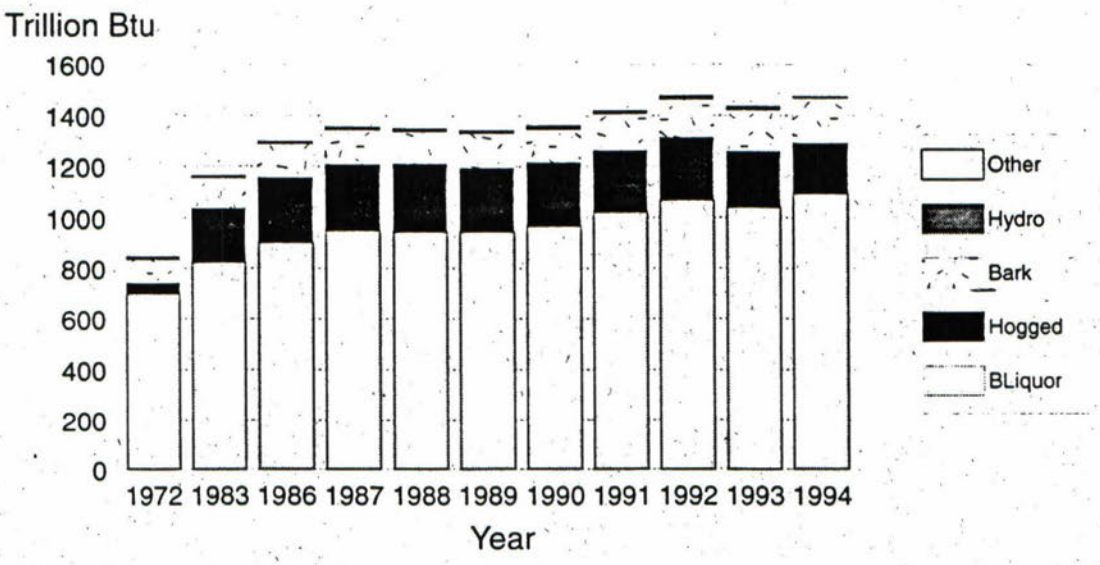
Source: Miller Freeman, Inc. (1972–1994)

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

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

Two opportunities for further improvements were analyzed in detail: increased self-generation from black liquor and increased recovery of usable energy from hog fuels and bark coupled with increased recovery of forest residues and pre-commercial thinnings. Increased self-generation offsets purchases of electricity and coal, and thus offsets CO_2 emissions.[15] These higher-efficiency processes could also increase the industry's electricity production for return to the grid.

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



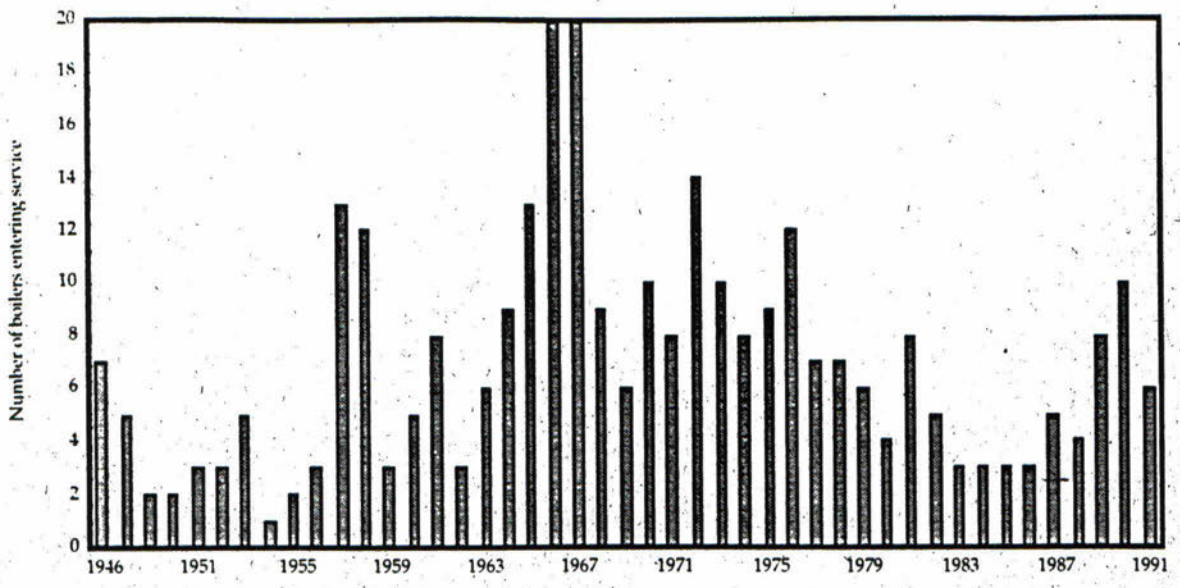
Source: Miller Freeman, Inc. (1972–1994)

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

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

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

Figure 4.8 Kraft Boilers in Service in the United States



Source: American Forest and Paper Association

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

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

Residual Biomass Boiler Replacements. Food processing, wood products, and pulp and paper are industries that generate large amounts of residual biomass (e.g., waste wood and bark). While much of this biomass is currently being used, if it were gasified and used to cogenerate steam and electricity, it would substitute for (largely) fossil fuel-produced electricity. Advances in turbine efficiency (see Section 4.3.2.1) make this an economically attractive option. By using residues from pulping processes as well as biomass from forestry operations in conjunction with gasification and combined cycle

technologies, 2.3 GW of capacity can be put in place by 2010, offsetting 4.8 MtC equivalent per year. This would represent about one-third of the potential mill conversions projected to need replacement by that time. Because of the stage of development of the technology and its markets, a conservative estimate would reduce replacements from one-third to one-quarter of the potential mill conversions. Using the more conservative penetration, the carbon replacement potential from gasification of residual biomass is 3.6 MtC equivalent per year.

Approximately 200 mills are already producing heat and some power from the use of residual biomass in their processes.[16] The majority of in-place boiler units entered service between 1965 and 1975 and need replacement; they are either reaching the end of their service lives or they may have difficulty meeting environmental regulations (or both). Residual biomass gasification can penetrate this replacement market with the potential to double the net rate of electricity generation – from a generation efficiency of about 15% to 35%. The technology is already in the early stages of commercialization with the first 18 MW IGCC operating in Sweden. Prototype units are being demonstrated elsewhere in Scandinavia and the United States.

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

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

4.3.4 Low Process Carbon Technologies

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

4.3.4.1 Industrial Sources of Non-CO_2 Greenhouse Gasses

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

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

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

- Waste emissions of SF_6 from the manufacture of transformers, circuit breakers/load-shedding devices, and electrical distribution components where SF_6 is used as an insulator;
- By-product emissions of N_2O from adipic acid manufacture;[17]
- Waste methane emissions from production of ethylene and styrene;
- PFC emissions from aluminum production (see Section 4.3.4.3); and
- Waste emissions of SF_6 from magnesium casting in which SF_6 is used as a cover gas to protect against catastrophic oxidation.

Table 4.13 Process Carbon Emissions and Energy Use by Sector

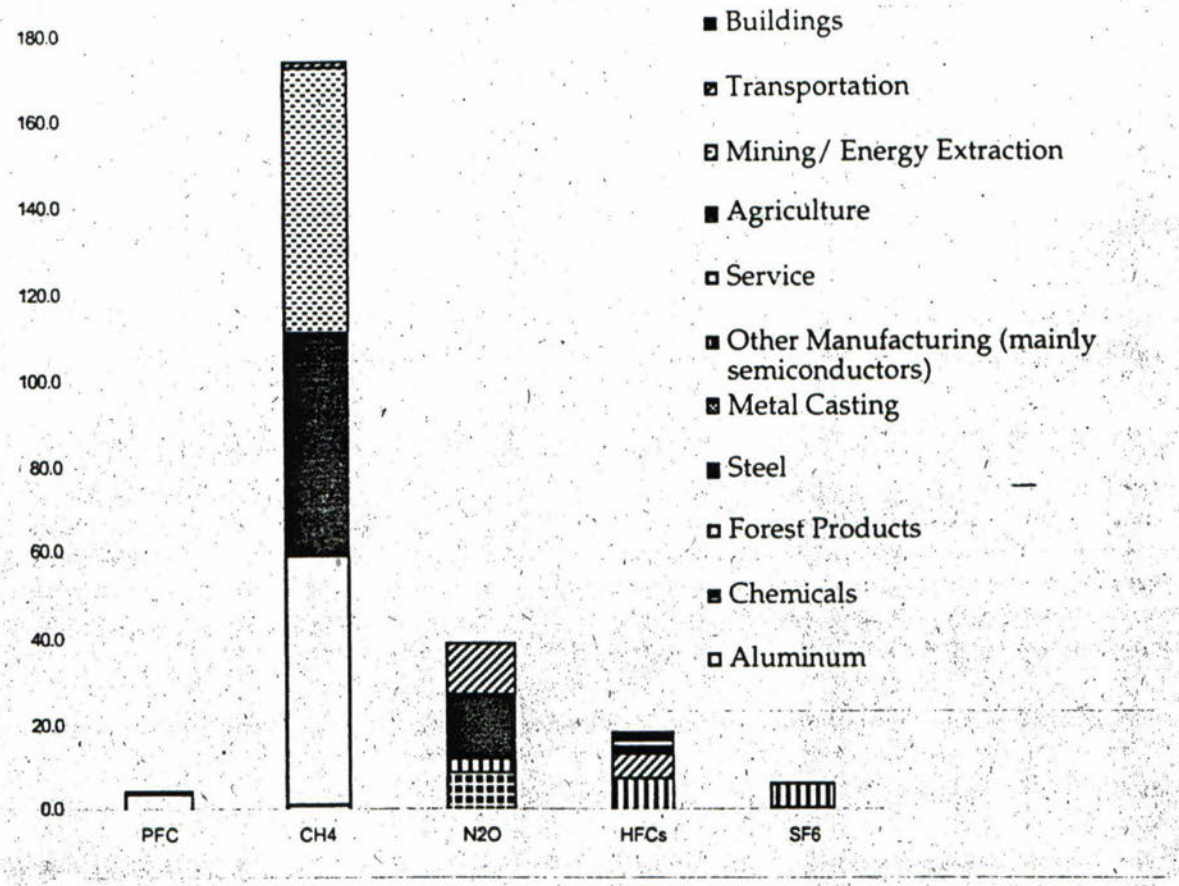
	Carbon Emissions (MtC equivalent)			
	Process CO_2*	Other GHG Carbon Equivalent	Total Carbon	Energy Use (quads)
Manufacturing	18.4	33.0	51.4	22.4
Service	0	58.2	58.2	
Agriculture	0	66.7	66.7	
Mining/Energy Extraction	0.9**	61.5	62.4	
Construction	2.0	0	2.0	
Subtotal Industry	**21.3**	**219.4**	**240.7**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

*Source: EIA 1996

**Gas flaring.

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

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



Source: EIA (1996)

4.3.4.2 Process CO_2 Emissions

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

The primary industrial processes that generate process carbon emissions include:

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

- Gas flaring; and
- Aluminum production.

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

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

4.3.4.3 Low-Carbon Technologies in Primary Aluminum Production

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

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

- First, carbon dioxide is generated at fossil fuel plants that produce the electricity required for the electrolysis process.[18] State-of-the-art Hall-Heroult cells achieve power consumption levels as low as 13,200 kWh/tonne of aluminum produced; however, most aluminum plants require more electricity per tonne of product.
- Second, the production of one metric ton (or tonne) of aluminum leads to the generation of at least 1.22 tonnes of process carbon dioxide (or 0.33 tonnes of carbon) from the reduction cell operation.
- Third, global warming effects also result from the generation of perfluorocarbons (CF_4 and C_2F_6) during instabilities in the cell operation (called "anode effects") that occur when oxide concentration in the cell bath becomes undesirably low. In 1994, aluminum smelting is estimated to have emitted the equivalent of 4.2 million metric tons of carbon equivalent, from perfluorocarbon (PFC) byproducts (EIA 1996).

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

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

On the basis of ongoing research on aluminum reduction technology, the desired improvements will require the development and commercialization of retrofit advanced cell technology with wettable

cathode and inert anode components. Two scenarios have been developed: an efficiency scenario, based on the development and use of wettable cathodes with conventional carbon anodes, and a high-efficiency/low-carbon scenario, based on the addition of inert anodes to the advanced cell.

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

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

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

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

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

Under the efficiency scenario, we assume that five of the existing 22 aluminum plants operating in the U.S. (American Metal Market 1997) are retrofitted to use the advanced wettable cathode cell. With an average plant capacity of 190,000 tonnes of aluminum per year and an average annual electricity

consumption of 13,200 kWh per tonne of aluminum, electricity efficiency improvements of 17% in these five plants would result in 0.19 million tonnes of reduced carbon-equivalent emissions in 2010.[19] This is 0.09 MtC more than the efficiency scenario described in Section 4.2.2.[20] In addition, the PFC emissions from anode effects are projected to be halved in those five plants where wettable cathodes are installed. This would represent an 11.4% (or 0.48 MtC) reduction in the aluminum industry's carbon equivalent emissions of 4.2 MtC.[21]

Under the high-efficiency/low-carbon scenario, use of the advanced, inert anode by 10 of 22 plants could lead to reduced carbon emissions by 1.6 MtC equivalent, of which 1.00 metric tonnes of carbon savings are due to the reduced consumption of electricity.[22] This is equivalent to 0.67 MtC over the high-efficiency/low-carbon scenario described in Section 4.2.2.[23] An additional 0.6 Mt of carbon savings result from the elimination of carbon emissions from the production cell.[24] The use of inert anodes to eliminate the process CO_2 emissions from smelting was not considered in Section 4.2.2; thus, all of these carbon reductions are accounted for here. In addition, the PFC emissions from anode effects are projected to be eliminated in those 10 plants where inert anodes are installed. This would represent a 45.5% (or 1.91 MtC) reduction in the aluminum industry's carbon equivalent emissions of 4.2 MtC.[25]

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

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

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

4.3.4.4 Replacing Cement Clinker with Solid Wastes

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

Nearly all cement in the United States is made from ground clinker intermixed with gypsum. One technically straightforward and cost-saving way to reduce energy input and carbon emissions per ton

of cement is to replace some of the clinker with abundant utility and steel plant wastes such as fly ash or granulated blast-furnace slag. Such a replacement makes cement with somewhat different properties, but still a satisfactory building material. Most European countries allow such cements and have found that these cements last longer and are more tolerant to salt water than pure clinker cement. However, U.S. product specifications (Standard Specification for Portland Cement, ASTM C150) do not allow any extra ingredients in cements. These specifications are difficult to change because the small minority of those who might lose markets (e.g., non-integrated cement producers) can easily stop changes under the current system. A recent study (Sauer 1997) estimates that changing the U.S. specifications to permit inter grinding could reduce both energy and process CO_2 emissions by 5–20% per year by reducing demand. If the specifications were changed, it is likely the new technology could be rapidly adopted by U.S. cement manufacturers, especially the multi-national firms that are already using this type of cement in Europe. Under the high-efficiency/low-carbon scenario, the barriers to this technology could be overcome. In addition, there would be motivation to conduct further research, development and demonstration activities exploring a wide range of cement inter grinding materials and percentages and to ensure that they provide the same or improved performance. Based on these studies and assuming a low-carbon, aggressive R&D scenario, our estimate is that by 2010, 1–2 MtC equivalent of industrial carbon emissions could be avoided due to cement inter grinding and replacement.[26]

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

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

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

4.4 PROVEN INDUSTRIAL TECHNOLOGIES

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

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

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

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

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

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

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

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

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

4.4.1 Cross-Cutting Technologies

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

4.4.1.1 Combined Heat and Power

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

4.4.1.2 Motor Systems

Energy-efficiency opportunities associated with electric motor drives derive not so much from the replacement of motors with high-efficiency motors as from energy-conscious design throughout the system employing the motor drive. Such a systems approach (see Section 4.3.2) has also resulted in significant non-energy savings when motor systems are improved.[27] The system includes power supply lines, controls, motor feed cables, the electric motor, the drive and transmission system, and the driven load. Each of these system elements may present a significant opportunity to conserve energy.

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

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

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

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

4.4.2 Pulp and Paper

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

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

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

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

On-Machine Sensors for Paper Properties: The development of new sensors to provide real-time feedback on whether the process and product are within specification can save the energy of reprocessing off-grade material and allow the use of greater amounts of recycled fiber. With an on-line

sensor for strength properties the process variability can be reduced and greater proportions of recycled fiber utilized. A 10% reduction in refiner energy at a single mill saves more than 70 billion Btu/year. Reducing the normal off-grade production rate by 50% (from a typical 5% to 2.5%) can save an additional 118 billion Btu/year. If 300 plants adopted these sensors, the annual savings would be about 60 trillion Btu.

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

4.4.3 Chemicals

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

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

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

Advanced Distillation Control Techniques: Distillation in refining and chemical industries consumes 3% of total U.S. energy use, which amounts to approximately 2.4 quads of energy annually. In addition, distillation columns usually determine the quality of final products and many times

determine the maximum production rates. Distillation columns commonly use 30% to 50% more energy than is necessary to meet the product specifications. It has been estimated that an overall average 15% reduction of distillation energy consumption can be attained if better column controls are applied.

4.4.4 Petroleum Refining

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

4.4.4.1 Monitoring Overall Energy Performance

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

4.4.4.2 Utility System Improvements

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

4.4.4.3 Process/Equipment Modifications

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

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

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

4.4.4.4 Fluid Catalytic Cracking

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

4.4.4.5 Fouling Mitigation in Heat Exchangers

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

4.4.5 Glass

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

4.4.5.1 Oxy-Fuel Process

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

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

4.4.5.2 Advanced Burner Technology

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

4.4.5.3 Glass Batch/Cullet Preheater Technology

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

4.4.6 Aluminum

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

4.4.6.1 Improving Hall-Heroult Cell Efficiency

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

4.4.6.2 Materials Recycling

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

4.4.6.3 Improve Furnace Efficiency

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

4.4.7 Iron and Steel

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

4.4.7.1 Direct Smelting / Direct Reduction

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

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

4.4.7.2 Scrap Preheating

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

4.4.7.3 Hot Connection

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

4.4.7.4 Near Net Shape Casting

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

4.4.8 Metal Casting

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

4.4.8.1 Computer-Aided Casting Design

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

4.4.8.2 Optimized Coreless Induction Melting

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

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

The technologies cited above are currently available, or soon will be, because of past R&D. For future technologies to contribute to increased energy and emissions reductions presumes a continued stream

the process is now available to be optimized for possible scale-up to pilot plant scale. It is estimated that, by the year 2020, this technology can provide annual energy savings of 12 trillion Btu (DOE 1997). While this is a modest total savings (the chemical industry used over five quads in 1991), this is just one of tens of thousands of chemical processes.

4.5.2.2 Flexible Chemical Processing of Polymeric Materials

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

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

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

4.5.2.3 Genetic Engineering

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

4.5.3 Petroleum Refining

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

4.5.3.1 Development of Improved Catalysts

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

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

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

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

4.5.4 Glass

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

4.5.4.1 Optimizing Electric Boost to Reduce Total Energy Consumption

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

4.5.4.2 Recovering and Reusing Waste Heat from Oxy-Fired Furnaces

Recovery and reuse of waste heat from the oxy-fuel process will further increase energy efficiency of the process. Preheating the batch and cullet, described above, is one method to recover heat from the flue gas. Other options, such as regenerative oxygen heat recovery (Browning and Nabors 1996) and a "synthetic air" concept (Argent 1997), have been proposed and need to be tested and evaluated. A Thermal Swing Adsorption (TSA) oxygen production process has been demonstrated in the laboratory

with enrichments of up to 89%. The process is based on synthetic chemicals that can reversibly bind oxygen at low temperatures and release it at elevated temperatures. The operation is in a temperature range of 70° to 220°F, so low grade waste heat can be used to drive the process, and the external energy required for produce oxygen can be reduced.

4.5.5 Iron and Steel

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

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

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

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

4.5.6 Metal Casting

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

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

EM Stirring: In continuous casting, the solidification process can be improved by EM stirring, producing better metallurgical results, improved internal quality of the casting, and even reduced meniscus instability and surface defects (Beitelman and Mulcahy 1994, Chang et al. 1995). The benefit

from EM stirring takes the form of reduced wastage per cast. As a minimum, we expect that the present average yield of 55% for the industry can be increased to 65%, a savings of 130,000 tons per year, with an associated energy savings of 25 trillion Btu per year (American Foundrymen's Society 1995).

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

4.6 CONCLUSIONS

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

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

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

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

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

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

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

Table 4.15 Summary of Technology Examples

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

* Based on the accelerated deployment described in Section 4.3.

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ENDNOTES

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

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

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

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

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

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

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

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

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

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

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

[12] See Appendix D-3 for details.

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

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

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

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

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

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

[19] 0.2 MtC = [(5 plants) * (190,000 tonnes of AL/plant)* (13,200 kWh/tonne of AL) * (89 gr of carbon per kWh) * 0.17]/1,000,000 grams/tonne.

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

[21] 0.48 = (5 of 22 plants) * (50%) * 4.2 MtC.

[22] 1.0 MtC = [(10 plants) * (190,000 tonnes of AL/plant)* (13,200 kWh/tonne of AL) * (160 gr of carbon per kWh) * 0.25]/1,000,000 grams/tonne.

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

[24] 0.6 MtC = (10 plants) * (190,000 tonnes of Al/plant) * (0.33 tonnes of C/tonne of AL).

[25] 1.91 MtC = (10 of 22 plants) * (100%) * 4.2 MtC.

[26] Note that almost none of the carbon savings due to Section 4.2.2's high-efficiency/low-carbon (HE/LC) case should be subtracted from this amount. The clinker replacement is not an efficiency increase, but a demand reduction. Thus, the drop in carbon emissions is nearly additive. We subtracted a very small amount because of the 8.1% reduction in cement industry energy use under

the HE/LC scenario. The carbon savings due to a 5-20% reduction in demand is 2-4 MtC depending on the kiln technology. The amount we subtracted is about 5% of the total (0.06-0.08 MtC). If we assume that the penetration by 2010 is limited to the European owned firms (roughly half), then the carbon reduction is 1-2 MtC. Note that the HE/LC energy efficiency savings of Section 4.2.2 are equivalent to a carbon emissions reduction of just over 1 MtC depending on cement kiln technology.

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

Chapter 5

TRANSPORTATION SECTOR

5.1 INTRODUCTION

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

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

- Between 1973 and 1988, new passenger cars increased their fuel economy from about 14 MPG to 28.6 MPG (EPA rated) (Heavenrich and Hellman, 1996, Table 1).
- 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% (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% of the period's MPG gain was achieved by shifts to smaller cars (Westbrook and Patterson, 1985). Between 1976 and 1989, the combination of weight reduction, improved transmissions, tires, and aerodynamics, widespread use of fuel injection, various engine improvements, improved lubricants, and wider use of front wheel drive accounted for about 70% of the total 8.4 MPG improvement during the period (Westbrook, 1989). In fact, the technology of automobiles has improved so much over the past few decades that if the 4,000 pound plus, 15.8 MPG automobile of 1975 were to be built with today's technology but *without any change in weight or horsepower*, it would get 26.4 MPG (Greene and Fan, 1994)! And although 85% of the improvement in rail freight energy efficiency came from increased loadings per car, much of the 85% resulted from improved communications and computing capability (other factors included changing composition of freight during this period and other operational improvements), and improved vehicle technology accounted for the remaining 15% (Greene, 1996).

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

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

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

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

engines including diesels and direct injection stratified charge engines), and improved electric drives, including power electronics.

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

The efficiency and high-efficiency/low-carbon scenarios differ from each other less in effort than in outcome. In our view, the improvements postulated in the efficiency scenario are *likely* to be forthcoming if appropriate policy measures are undertaken and research efforts intensified. In contrast, because the outcomes postulated in the high-efficiency/low-carbon scenario require technological breakthroughs, they require a certain degree of luck to be achieved by 2010. There are no credible methods to accurately gauge the probability of such breakthroughs; we believe they stand a decent chance of occurring with an intensification of research efforts, but we stop short of claiming that they are a likely outcome of such an intensification.

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

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 compared to petroleum-based fuels. The more breakthroughs one assumes, however, the lower the probability that the scenario will actually occur. Furthermore, in the long-run, no single technology appears to have a greater potential to reduce carbon emissions from transportation than the fuel cell.

Although the focus of this study is on the year 2010, forecasts to 2015 are also presented because changing the technology of transportation energy use takes more than one decade. Once a technology is market ready, two to three years of testing and certification are still required prior to introduction. Even then, most technologies will not appear on all makes and models simultaneously due to the need to replace plant and equipment in an efficient manner. Finally, expected lifetimes for transportation vehicles are counted in decades. The median expected lifetime of a passenger car

is now 14 years, truck lifetimes average 16 years, marine vessel and aircraft life expectancies are at least twice that (Davis and McFarlin, 1996, Tables 3.6 and 3.7). Thus, the full impact of technologies introduced between now and 2010 will not be apparent in 2010. We include the year 2015 to illustrate this fact. In all cases, a normal rate of replacement of capital stock is assumed, both in the production of transportation vehicles and in their purchase and scrappage. That is to say, no changes are made to the NEMS model to accelerate the turnover of capital stocks.

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

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

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

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

We wish to emphasize that, in our judgment, the reductions in carbon emissions described in these scenarios are unlikely to be achieved by advances in technology alone, in the absence of meaningful additional policy measures to insure that cost-effective and near cost-effective technologies to improve energy efficiency and to expand the production of biomass fuels are in fact implemented. This is not only our conclusion. The 1995 Asilomar Conference on Energy and Sustainable Transportation, organized by the National Research Council (NRC), Transportation Research

Board's Committees on Energy and Alternative Fuels, addressed the question, "Is technology enough to achieve sustainable transportation?" The conference's consensus, to be published in a forthcoming volume of proceedings, was that technologies capable of creating a sustainable transport system could be developed over a reasonable time period but that the marketplace on its own would be unlikely to adopt such technologies in the absence of specific policy measures to make it happen (McNutt et al., 1997). Because of the inertia inherent in the nation's transportation system, and because reducing greenhouse gas emissions is a public good, meaningful policy action is likely to be essential to achieving the carbon emissions reductions described in these scenarios.

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

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

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

5.2 PROVEN AND ADVANCED TECHNOLOGIES

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

There is wide agreement that new efficiency technologies will continue to enter the fleet and that technologies recently entered will gain market share. Table E.1 in Appendix E lists those

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

5.2.1 Material Substitution

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

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

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

5.2.2 Aerodynamic Drag Reduction

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

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

need for high ground clearance and large tires, open beds in pickup trucks, and so forth. Also, the short length of subcompact autos limits the degree to which their C_d can be reduced.

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

5.2.3 Improved Automatic Transmissions

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

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

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

5.2.4 Engine Friction Reduction

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

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

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

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

5.2.5 Variable Valve Timing

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

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

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

5.2.6 Lean-Burn Engines

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

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

5.2.7 Advanced Tires

Rolling resistance accounts for approximately a third of the loads on an automobile during the EPA test procedure. The magnitude of this resistance is approximately linearly related to the rolling

resistance coefficient of the vehicle's tires, so reducing this coefficient through changes in tread design, tire materials, and tire structure will have a significant positive impact on fuel economy.

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

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

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

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

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

5.2.8 Advanced Drag Reduction

In our view, significant market pressure on fuel economy could reduce C_d values a bit further than projected by the auto makers. Some existing vehicle designs that have attained lower C_ds without some of the design compromises of the prototypes noted above indicate that a C_d of 0.22 should be practical for a mid-size car without requiring wheel skirts or a sharply tapered rear end. This

value has been adopted as successfully entering the mass market automobile fleet in both the efficiency and high-efficiency/low-carbon scenarios, and is modeled as an additional 10% reduction in drag over the lowest C_d value in NEMS of 0.245.

5.2.9 Hybrid-Electric Power Trains

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

- They offer the potential to recapture some of the vehicle's potential energy that is normally lost (as heat) when the vehicle is braked. In a hybrid, the electric drive motor can be operated in generator mode to brake the vehicle; the electric energy produced is stored in the battery or other storage device.

- The hybrid drivetrain allows the vehicle powerplant to be smaller and to operate more efficiently than the powerplant in a conventional drivetrain. In a conventional drivetrain, the engine is sized for the maximum load (usually short-term rapid acceleration) and can produce many times the power it uses during the great majority of its operation. For example, during idle, low speed cruise, or deceleration, the powerplant may be operating below 10% of its maximum power capability, and most engines (especially gasoline engines) are very inefficient at such lower power levels. Because the storage device can absorb any excess power (over that needed to operate the vehicle) produced by the engine, the engine can continue to operate at an efficient power level even when the vehicle loads are low. Also, in a hybrid, the storage device can provide part of the power for maximum acceleration, allowing the hybrid powerplant to be sized for average power requirements or for power requirements in operations where the battery can't help (e.g., during sustained hill-climbing), which are generally lower than acceleration loads – so the hybrid's engine can be smaller.

The net energy gains from the regenerative braking, smaller and lighter powerplant, and improved powerplant cycle efficiency are counteracted by losses in the electrical components (storage device, generator, motor/controller) and their added weight (in particular, weight of the storage device and electric motor). The wide variety of hybrid configurations and component designs, the relatively early stage of development of hybrid powertrain systems, and the ongoing redesign of hybrid powertrain components to satisfy the unique requirements of hybrid operation has yielded a wide range of estimates of the potential efficiency benefits of shifting to hybrid drivetrains. Further, ongoing changes in engine design for conventional drivetrains shift the relative value of hybridization, with reduction in pumping losses achieved by variable valve control, for example, reducing the benefit of hybridization because these are the same losses hybridization is designed to counter. The OTA has estimated that a battery/ICE hybrid can achieve about a 25-35% gain over a conventional drive vehicle with the same type of powerplant, assuming what it considered optimistic values for the efficiencies of the battery and electric motor (U.S. Congress, OTA, 1995). Current examples of operating hybrids that satisfy normal vehicle safety and performances requirements[4] have not achieved efficiency improvements this high (U.S. Congress, OTA, 1995). On the other hand, the Department of Energy's (DOE's) goal for its hybrid drivetrain R&D program is a doubling of fuel economy, and theoretical analyses of hybrid configurations using simulation models have projected gains ranging as high as the DOE goal (Burke, 1995; Ross, 1996). In our view, gains this high are unlikely without sacrificing some aspects of performance or operational flexibility.[5] On the other hand, there are active R&D efforts on hybrid components such as ultracapacitors and high-efficiency electric motors that, if successful, could raise the efficiency advantage of hybridization to somewhat higher levels than OTA projects. The efficiency case

conforms approximately to the OTA projections; the high-efficiency/low-carbon case assumes exceptional success at improving drivetrain components and reducing costs. This translates to a 28% fuel economy benefit over a 1995 conventional gasoline-fueled car, and a 10% benefit over a DI diesel vehicle for the efficiency case; in the high-efficiency/low-carbon case, the assumed gains are 43% and 23%, respectively.

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

5.2.10 Direct Injection Stratified Charge (DISC) Gasoline Engines

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

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

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

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

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

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

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

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

5.2.12 Proton Exchange Membrane (PEM) Fuel Cell Powertrains

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

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

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

Key needs are development of low-cost membranes, size and cost reduction of hydrogen reformers or onboard storage, and improvement of "balance of plant." Also, there are several engineering issues that will have to be dealt with once stack design has gotten to the point where serious vehicle design is contemplated – for example, cooling the low temperature operation of fuel cells