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Energy Efficiency: How Far Can We Go?

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MARTIN MARIETTA ENERGY SYSTEMS, INC.
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Conservation and Renewable Energy Program

ENERGY EFFICIENCY: HOW FAR CAN WE GO?

A Study By The Staffs Of

The Oak Ridge National Laboratory
The Argonne National Laboratory
The Lawrence Berkeley Laboratory
The Pacific Northwest Laboratories
The Idaho National Engineering Laboratory

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I. SUMMARY AND CONCLUSIONS

Since 1973, U.S. energy use has increased only 8 percent while GNP increased 46 percent, indicating a substantial increase in the efficiency of energy use. However, the decline in oil and gas prices since 1985 seems to have resulted in stagnant energy-use efficiencies. This study examined prospects for resumption of efficiency gains during the next 20 years.

Two scenarios were studied. In the first, we estimated likely future trends in end-use energy efficiency, given an assumed course of events in population growth, economic growth, and fuel prices. This scenario is entitled "Where We Are Headed." In the second scenario, we estimated the larger gains that might be obtained if advantage were to be taken of efficient, cost-effective technologies in new installations and replacements. Energy consumption in these two scenarios was then compared with the energy consumption that would result from "frozen efficiencies" in the various end uses.

Results are displayed in Fig. I-1.

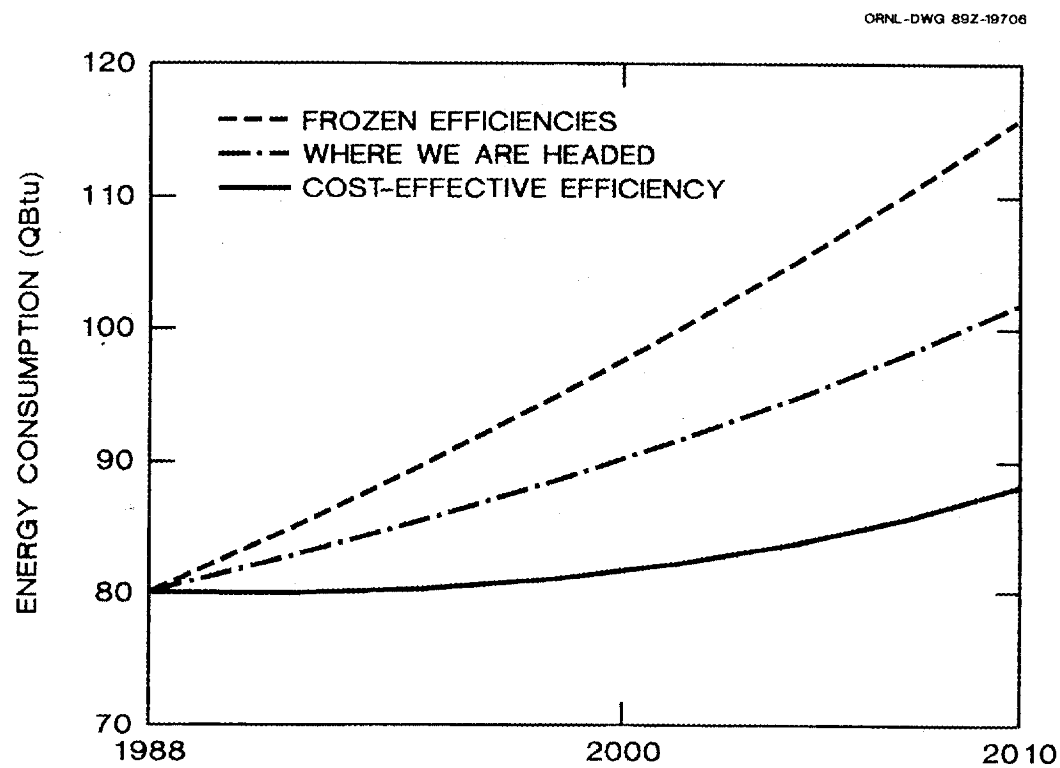

Fig. I-1. Study results.

The curve of frozen energy efficiencies, which reaches 115 QBtu in 2010, is our estimate of the rate at which U.S. energy demand would grow if there were no changes in the existing stock of equipment and structures, and no changes in energy use. (Frozen efficiency is used as a yardstick against which changes in energy efficiency can be measured rather than providing a scenario.) It should be noted that most energy-intensive activities are growing less rapidly than other sectors of the economy. Hence energy use will grow more slowly than GNP even if the efficiencies of energy-consuming equipment and energy use do not change.

In Fig. I-1 the curve of "Where We Are Headed," reaching 102 QBtu in 2010, is our projection of what is likely to happen, given the assumed fuel prices and economic variables and no change in energy policy. This scenario implies a 12 percent improvement in energy efficiency compared to frozen efficiency.

The curve of "Cost-Effective Efficiency," reaching only 88 QBtu, is our estimate of the end-use energy efficiency that could be economically achieved by 2010, given the same price and economic assumptions as in the previous scenario. For this computation we assumed a discount rate of 7 percent real. Neither of the two scenarios includes efficiency improvements in energy conversion, such as electricity production, transmission, and distribution.

Efficiencies considerably greater than in either of the two scenarios are technically feasible through the use of technologies with higher first cost than those we considered. It is often argued that the use of such technologies is warranted by the national security implications of our increasing oil imports and by the environmental impacts of our increasing fossil fuel use.

In particular, restrictions on carbon dioxide emissions to avoid global warming problems could introduce major perturbations to the projections. As a consequence, the cost of fossil fuels and electricity would increase, and energy-efficient technologies would be adopted at an accelerated rate.

Principal conclusions from the study are the following.

- Substantial improvements in energy efficiency (about 12 percent) will occur by 2010 through the operation of market forces if fuel prices rise as projected.
- Substantial additional improvements in energy efficiency (an additional 14 percent) would be cost-effective but will not occur without extensive policy changes.
- Additional potential for efficiency improvements beyond 2010 is very large, but much of it will not be realized without concerted research and development efforts by government and industry.
- Our overall estimate of where we are headed agrees well with other recent baseline estimates.
- Estimates of additional cost-effective potential vary widely, but all investigators have found that the potential is large.
- An important uncertainty in our estimates derives from uncertainty in future fuel prices. In addition, our study suffers from the shortcoming of ignoring the effect of reduced energy demand on energy prices.
- Serious uncertainty in our detailed estimates (for example, particular end uses) derives from lack of sufficient attention in recent years to data collection, model development, and program evaluation. Although good models were available for some subsectors, judgmental estimates were required for others. Our models failed entirely to include some technologies for increasing energy efficiency.

II. INTRODUCTION

The United States has made remarkable progress in efficient energy use since the 1973 oil crisis. In 15 years energy use increased only 8 percent, while gross national product increased 46 percent.[1] Thus we are now using 26 percent less energy to produce one dollar's worth of goods and services. Some of this reduction came from structural changes in the economy, but most of it resulted from increases in energy efficiency.[2] The experience shows that threats of shortages, rising prices, and government policies can make major changes in the operation of the economy.

The questions we now face are the extent to which these trends in energy efficiency are likely to continue, and the factors that will influence them. On the one hand, overall energy efficiency has hardly changed since oil prices dropped precipitously in 1986. On the other hand, detailed studies of energy technologies all point to large opportunities for more efficient energy use, even at current fuel prices.[3] Furthermore, it is frequently noted that other industrialized nations (with generally higher energy prices) use energy more efficiently than the United States.[4]

A review of these questions was undertaken by the staffs of five national laboratories during the summer of 1989. We undertook the review at the request of the Office of Policy, Planning and Analysis in the Department of Energy. Our purpose was to provide background information needed by the Department in formulating a new national energy strategy. A ground rule of the review was that changes in government policy were not to be considered, since later phases of the national energy strategy process will examine these issues. Our review covered only end-use consumption of energy (residential, commercial, transportation, and industrial sectors), and thus omitted the significant efficiency improvements that can be made in the generation, transmission, and distribution of electricity. This report summarizes the results of the review.

First, we asked how much end-use efficiency improvement is likely to occur between 1990 and 2010. In this part of the analysis we assumed continuation of present trends in construction, equipment manufacture, and personal lifestyles. We assumed that fuel prices, population, and economic activity will follow the paths forecast by the Energy Information Administration[5] (EIA) as of mid-1989. We also assumed no changes in the governmental regulations, tax policy, and incentive programs that affect energy use. Although we do not expect all (or even most) of these assumptions to be realized, the conditions of this scenario should give a reasonable indication of energy consumption over the next 20 years if there are no unexpected changes in economic factors and no changes in government policy. Results of this "business as usual" scenario are given in Chapter III, "Where We Are Headed."

Next, we estimated the technical potential for cost-effective improvements in energy efficiency between 1990 and 2010 (that is, those that cost less money than they save). The computations for this scenario were made as if purchasers of energy-related equipment consider life-cycle cost with a discount rate of 7 percent real. The 7 percent discount rate was chosen as an approximation of a socially optimal allocation of resources. One would expect this scenario to yield considerably greater energy efficiency than the previous one, since it has often been noted that our current energy use is considerably higher than it would be if the best available technologies were universally used. For instance, central air conditioners are now available with seasonal energy efficiency ratios (SEER) as high as 15 while the average unit sold has an SEER of only 9. (ref. 6) For this scenario we postulated that the most cost-effective technologies would be installed as new and replacement equipment is needed, and as new technologies become commercially available. Thus we allowed for realistic replacement schedules of the existing stock of factories, vehicles, and buildings over many years. Although we included both presently available technologies and new technologies now under development, the former are likely to be most significant during the next 20 years. As noted above, we did not analyze the changes in attitudes, behaviors, policies, and standards that would be required to move our economy from the business-as-usual scenario to this energy-efficient scenario. Results of the "energy-efficient" scenario are given in Chapter IV, "Cost-Effective Efficiency."

Why are we using energy inefficiently, when efficient technologies would give the same energy services and save money while, at the same time, reducing environmental problems, increasing national security, and increasing industrial competitiveness? Research in recent years has identified some factors that explain the discrepancy between current practice and efficient use of energy and capital. These are discussed in Chapter V, "Closing the Efficiency Gap: Barriers to Improving Energy Efficiency."

Finally, our review looked at the more distant future. The next 20 years will see the introduction of many new technologies, but the following periods could see more radical changes in the ways we use energy. In Chapter VI, "Extending the Limits," we examine the role of research and development in making our energy system more efficient.

III. WHERE WE ARE HEADED

Aggregate statistics indicate that the pace of efficiency improvements in the United States has slowed or perhaps stopped. Nevertheless, there are numerous examples of continuing improvements. New homes are being built to tighter standards than the older buildings they replace. New automobiles have better fuel economy than the fleet average. Recently enacted federal energy standards for home appliances will require manufacturers to increase efficiency. Other developments, however, such as more stringent environmental controls and the increasing size of automobiles, may foreshadow decreases in efficiency.

In this chapter we sum up where we appear to be headed in the next 20 years (1990 to 2010) in the absence of specific efforts to increase energy efficiency. The scenario assumes that there are no changes in government energy regulations or industry standards beyond those already agreed upon. We also assume no changes in government subsidies, tax policies, or incentive programs. New technologies are introduced into the scenario at rates that appear reasonable, considering their present state of development. We use the schedules of future fuel prices and economic growth suggested by EIA in its base case forecast.[1] The EIA schedules specify a 2.5 percent annual increase in GNP, a substantial increase in prices of petroleum products (for example, motor gasoline goes from 0.86 1988 dollars per gallon in 1990 to $1.87 per gallon in 2010), while electricity prices are essentially constant (see Appendix B). We do not expect all of these assumptions to be realized. However, the results of the scenario give an indication of what the future may look like if policies are unchanged and economic conditions develop as predicted.

We focus our attention on projections of energy consumption in the three end-use sectors—buildings, transportation, and industry. We then examine indicators of energy efficiency in the principal subsectors. As noted previously, we have not included efficiency improvements in the electric utility industry and therefore omit one important area for reducing energy consumption.

BUILDINGS

The buildings sector accounted for 65 percent of U.S. electricity consumption and 48 percent of natural gas consumption in 1988. Buildings have accounted for an increasing share of national energy consumption, rising from 33 percent in 1979 to 36 percent in 1985.[2] At the same time, energy intensity in residential buildings has improved from a high of 217 million Btu per household in 1972 to 180 million Btu in 1985. Energy costs in buildings were $173 billion in 1985, while the value of new construction was $355 billion in 1985.[3]

Future U.S. energy consumption in buildings will depend upon population growth, economic conditions, and energy prices. From 1990 to 2010, the number of households is expected to increase by 32 percent, and commercial floor space is expected to increase by 47 percent. Total residential energy consumption is expected to grow about 18 percent, or about 0.8 percent per year. Total commercial energy consumption is expected to grow about 44 percent, or about 1.8 percent per year.

The fraction of total primary energy consumed in the buildings sector to be supplied by electricity is expected to grow from 63 percent in 1990 to 76 percent by 2010, corresponding to an average growth rate in electricity demand of 2.2 percent per year.

Projections of energy consumption for residential buildings were made using the Lawrence Berkeley Laboratory Residential Energy Model (LBL-REM).[4] Commercial building projections were prepared with the National Commercial Energy Model maintained by Pacific Northwest Laboratories.[5]

Energy intensity in residential buildings is expected to decline from 180 million Btu per household in 1990 to 162 million Btu per household in 2010. Much of the decline is due to national appliance energy efficiency standards, which increase the efficiency of new appliances starting in 1990. Additional improvements reflect the continuing gradual penetration into the market of other cost-effective efficiency measures, such as building shell improvements. In commercial buildings, energy intensity is expected to decline from 206 thousand Btu per square foot in 1990 to 201 thousand Btu per square foot in 2010. The slow change in energy intensity for commercial buildings reflects the expected stability of electricity prices, and the net effect of increasing electrification (for example, computers and telefax machines) working against increasing market-based efficiency improvements. In fact, the intensity will decline more than this, once account is taken of national efficiency standards affecting fluorescent light ballasts.

Major shares of energy consumption in buildings in 1990 are attributable to space heating (42 percent of primary energy), lighting (15 percent), water heating (12 percent), and air conditioning (8 percent). Miscellaneous end uses account for the remaining 23 percent.

Air conditioning, lighting, and miscellaneous energy combined are projected to increase their share of annual energy in buildings from 46 percent in 1990 to 50 percent in 2010. Water-heating energy is expected to retain a 12 percent share. Space heating is responsible for a decreasing share, down from 42 percent in 1990, to 39 percent in 2010. The greatest decrease in share is expected for household refrigerators/freezers, which decline from 11 percent of annual residential energy in 1990 to 9 percent in 2010.

Total energy consumption in buildings is expected to grow from 30.3 QBtu in 1990 to 39.2 QBtu in 2010 (see Table III-1 and Appendix C, Table C-1).

TRANSPORTATION

To place the role of attaining efficiency in the transportation sector into perspective, it is important to understand that petroleum has been and continues to be the only economical transportation fuel. Although progress is being made in making alternative transportation fuels economically attractive, at current oil prices such fuels capture only very limited market niches. As a result, efficiency improvements have been the major method of reducing transportation petroleum use.

Although passenger cars obtained 18 percent better fuel economy and per car driving dropped by 4 percent, transportation as a whole contributed only 18 percent of the 7.9 QBtu decline in oil use from 1978 to 1983. By contrast, transportation accounts for over 62 percent of U.S. petroleum consumption. Moreover, in the decade ending in 1988, there was an increase of over 30 percent in consumption of aviation and diesel fuels. The latter increase occurred in spite of declines in

Table III-1. Where we are headed in buildings energy[a]

	1985	1990	2000	2010
	Energy consumption (QBtu)			
Residential	16.0	17.2	18.4	20.4
Commercial	10.8	13.1	16.0	18.8
Total	26.8	30.3	34.4	39.2
	Energy intensity			
Residential (MBtu/household)		180	166	162
Commercial (kBtu/ft^2)		206	204	201

[a]Energy use in this report is given in units of QBtu (1 QBtu = 10^{15} Btu). Electricity is converted at 11,200 Btu/kWh, and thus includes losses in generation, transmission, and distribution.

demand for refined oils by both railroads and vessels. Accordingly, trucks accounted for the increased demand for diesel fuel. The increase in diesel fuel use was made worse by the fact that trucks exhibited the smallest improvement in fuel economy per unit of service over the period 1975 to 1985 as compared to jet aircraft, passenger cars, and railroads. The sharp increase in energy use by jet aircraft was due to expansion in the number of passenger- and freight-miles flown.

Recent trends are a useful guide to near-term developments. Following the 1986 oil price collapse and subsequent shift in demand toward larger vehicles, members of the auto industry successfully appealed for a reduction in the corporate average fuel economy (CAFE) standard. As a result, the rate of gain in fuel efficiency dropped. The fuel economy of imported vehicles has declined since 1983, about two years after real gasoline prices peaked. The computer model used to project new car rated fuel economy and on-road household fleet economy translates the data from these trends into short-term (one to three years) and long-term (five to ten years) manufacturers' reactions to gasoline price changes. Oil price scenarios used in this study project stable real oil prices through the early 1990s, rising steadily to new world highs by 2010 (Appendix B). A set of computer models developed at the Argonne National Laboratory (ANL) was used to project transportation activity, household vehicle composition, personal and commercial energy use, and freight activity.[6]

The ANL computer models convert the EPA ratings of new car fuel efficiency into estimates of the actual fleet fuel efficiency. Patterson and Westbrook[7] have shown that increasing congestion has slowed average trip speed and led to a wider margin between EPA fuel economy and on-road experience. Patterson anticipates that the gap between EPA-rated fuel economy and on-road economy will widen from about 12 percent in the 1970s to over 30 percent by 2010 if current trends continue. This judgment has been incorporated in our models of auto and truck fuel use projection.

From 1983 to 1988, transportation increased its energy use at about 2.1 percent per year—motor gasoline use expanded at about a 2.0 percent rate, jet fuel use at 7.0 percent, diesel fuel use at 3.8 percent and use in ships at 0.4 percent.[8] At these rates, the annual growth of jet fuel consumption would overtake that of motor fuel (gasoline) in eight years. Thus we believe that additional attention should be focused on improving the fuel efficiency of the aircraft fleet and reducing inefficiency caused by congestion at airports. Unfortunately, we do not have a detailed model to address this aspect of the transportation energy problem. We have therefore used historical relationships, recent trends, and judgment to forecast aviation fuel use.

The original requirement to attain a 27.5 mpg fleet fuel economy for domestic passenger cars has been reinstated in the 1990 CAFE standard, and this change is included in our base case analysis. In spite of this change, the model we use predicts a 1.5 percent per year deterioration in new car fleet fuel economy from 1989 to 1992. This is consistent with recent trends. Oak Ridge National Laboratory[9] estimates indicate that since 1983 the mpg rating of new foreign cars has declined each year. This downward trend in fuel economy among vehicles capturing a larger share of the market has led to a decline in the estimated fuel economy of the new car and truck fleet in 1989, the first such decline since 1984.[10] After the low point in 1992, the steady rise in real gasoline prices takes hold and our estimate of EPA-rated new car fuel economy rises to about 42 miles per gallon in 2010, an average increase of 2.7 percent per year. This price-driven prediction compares to the 5.3 percent per year increase achieved from 1974 to 1988 under the combined influences of gasoline price rises, environmental regulation, and fuel efficiency regulation. This fuel economy improvement is induced by post-2003 real gasoline prices never before seen in U.S. history, but still well under those in Japan, Brazil, France, Denmark, and Italy in 1987, and comparable to those in England, India, and West Germany at that time.[11]

The consequences of these trends are rising consumption of motor gasoline through 1999. Thereafter, continuous increases in real gasoline prices start to push light-duty fleet fuel consumption down. These estimates are consistent with reactions to the overall 1973 to 1981 rise in real oil prices, which was followed by no growth in motor fuel consumption in the 1978 to 1988 decade.

Consistent with the earlier discussion about diesel fuel consumption in trucks, the growth of truck traffic (2.5 percent per year, 1995 to 2010) is greater than that of light-duty vehicles, while the fuel economy of trucks increases at a slower rate (0.8 percent per year, 1995 to 2010) than that of light-duty vehicles. As a result, energy consumption for hauling freight increases steadily throughout the projection period. For heavy-duty trucks our projections of potential efficiency improvements through off-the-shelf technologies are less optimistic than those for passenger cars. Unlike passenger cars, whose passenger and freight load is a reasonably small percentage of total on-highway weight, the passenger and freight load of heavy trucks is a large part of the weight of the vehicle. Thus, vehicle weight reduction is not a promising strategy for improving fuel efficiency in heavy trucks. Fuel efficiency in heavy trucks is now improving through increased penetration of available technologies such as cab-mounted air deflectors, fairings to reduce the gap between tractor and trailer, radial tires, high-torque low-rpm engines, variable-speed fans, improved lubricants, electronic transmission and engine controls, advanced methods for controlling aerodynamic drag, and better matching of truck specifications to missions.

Railroad fuel consumption is projected to buck the recent declining trend and to expand its share of the market for freight, partly due to its inherent efficiency. Since rail uses about one-fourth the energy per ton-mile compared to trucks, our computer model projects that high energy costs will force some reorientation from truck to rail in the trend toward "just-in-time" deliveries. Rail gains market share in this case because of its inherent efficiency, not because of greater improvements in efficiency than in other sectors. In fact, rail fuel efficiency is projected to improve at only about 0.3 percent per year from 1990 to 2010.

Relatively rapid growth in air travel, as compared to other forms of travel, is projected to continue in spite of rising fuel costs. Revenue passenger-miles are projected to increase at a rate of 3.2 percent per year. However, energy use by air travel is expected to increase by only 1.9 percent per year because of increasingly efficient aircraft engines and structures. Particular technologies include continued improvements in compressor and turbine efficiencies, increased use of composite structures (including metal matrix materials), and active controls.

Our projections capture automotive fuel efficiency in a general way, without detailing specific technologies. However, a survey of experts conducted by Patterson and Westbrook[12] predicts that many alternatives would be in the market by 2010 if gasoline prices rise to the levels in our baseline. The survey projects savings within the three categories of fuel efficiency, behavioral modification, and fuel substitution. According to the survey, fuel efficiency gains would include, among other things, contributions from automotive gas turbines, use of ceramics, low-heat-rejection diesel engines, and aerodynamic devices on trucks. Behavior change opportunities were estimated to be small, at about 0.07 QBtu for $1.50 gasoline. Substitution of electric vehicles, compressed natural gas vehicles, and methanol-fueled vehicles was estimated to lead to a significant 1.0 QBtu transportation oil use reduction if gasoline prices were $1.50, and 2.8 QBtu if prices rose to $3.00. Since prices in our scenario do not reach $1.50 until about 2005, and a lag should exist in the introduction of alternatives, we estimate that the use of alternative fuels could reduce transportation oil use by less than 1 QBtu by 2010.

In summary, total energy consumption in transportation is expected to grow from 20.1 QBtu in 1985 to 24.3 QBtu in 2010 as shown in Table III-2 (see also Appendix C, Table C-2). Efficiency of personal travel is expected to increase by 44 percent, while the efficiency of freight transportation increases only 11 percent.

Table III-2. Where we are headed in transportation energy

	1985	1990	2000	2010
Energy consumption (QBtu)				
Personal travel	9.2	9.9	10.1	9.3
Freight	6.2	6.9	7.8	9.2
Air travel	1.7	1.9	2.2	2.7
Other transportation	3.0	3.0	3.1	3.1
Total	20.1	21.7	23.2	24.3
Energy efficiency				
Automobile (mpg)	18.2	19.4	21.8	26.6
Personal light trucks (mpg)	14.5	15.4	16.7	19.7
Freight (TMT/kBtu)	0.68	0.68	0.72	0.75
Air travel (passenger-miles/kBtu)	0.16	0.18	0.21	0.25

INDUSTRY

Energy use patterns in U.S. industry have changed dramatically over the past two decades. Total industrial energy demand dropped from 32 QBtu in 1973 to 29 QBtu in 1988.[13] (See Appendix C, Table C-7). Energy efficiency improvements were most important in this change, reducing industrial energy demand in 1982 by an estimated 10 QBtu compared to 1982 estimated consumption at 1972 efficiency levels. Changes in industrial product demand were also important, reducing sectoral energy demand by about 5 QBtu. Imports shifted about 3 QBtu overseas. These factors more than offset an annual growth rate of almost 2 percent in industrial product output, largely because industrial energy efficiency improved by 2 to 3 percent per year between 1972 and 1985.[14] More recently, however, energy efficiency improvements have slowed or even reversed, contributing to a 3 QBtu increase in U.S. industrial sector energy demand from 1982 to 1988.[15]

The slowdown in energy efficiency is almost certainly due not to diminishing technical opportunities, but rather to factors such as declining energy prices and curtailment of government energy conservation programs. The potential for continuing efficiency improvements in industry has been demonstrated by many key studies.[16] In particular, engineering-oriented analyses, which focus on the technical and economic potential for efficiency, have suggested that the United States should be able to improve industrial energy efficiency through the year 2000 to 2010 at rates approaching those achieved over the past two decades. Macroeconomic and econometric approaches, however, tend to be pessimistic about the likelihood that this potential will be captured.

In projecting future industrial energy consumption we use a combination of engineering and economic approaches. We take into account factors such as energy prices, economic growth, structural change in the economy, and economic behavior. We apply a simple, parametric energy end-use model which estimates future energy demand as a function of economic growth; energy price; price-, income-, and cross-elasticities of demand; technical improvements in energy efficiency; and structural change.[17]

To project future rates of structural change, we relied in part on U.S. Energy Information Administration (EIA) estimates of industrial growth rates (relative to GNP) by sector.[18] We modified these, however, in cases where the information available to us suggested different assumptions. Our assumptions differ importantly from EIA's for primary metals, chemicals, and general manufacturing. EIA suggested that steel and aluminum output would recover from recent declines and grow at roughly seven-tenths the rate of the economy (see Appendix C, Table C-8). Analysts familiar with the industry, however, recommended much lower rates—even zero growth.[19] We assume that primary metals will grow only one-quarter as fast as the economy as a whole, which, though much smaller than the EIA assumption, nevertheless implies a reversal in the major decline of this industry over recent years. This assumption is justified in part because the steel industry—the largest consumer of energy in the primary metals sector—has indeed recovered somewhat in recent years, currently benefits from import restrictions, and has improved labor productivity, making it more competitive.

We expect much higher relative growth in other industries, particularly chemicals and paper. We project these industries to grow at or just below the overall economy. EIA, on the other hand, projected chemicals output to grow faster than the GNP. Similarly, we expect other industrial output to grow only eight-tenths as fast as the economy (see Appendix C, Table C-8). The main justification for choosing structural change assumptions different from EIA's is that we see no valid reason why long-term trends in the material intensity of the economy should be reversed. Rates of consumption of steel, aluminum, copper, and cement per unit of economic output have declined steadily over the last several decades.[20] This decline accelerated after the energy price shocks of the 1970s, partly because energy price increases made energy-intensive materials more expensive to produce. Also, the need to conserve fuel in automobiles led to marked reductions in the use of steel. Because we assume continuing energy price increases, we expect these trends to continue.

The possibility remains, of course, that the United States could resume rapid growth in energy-intensive materials production to satisfy growing export markets. However, this result assumes that the United States overcomes a major obstacle to international competitiveness: a dollar made strong in foreign exchange markets by federal deficits and the trade deficit itself. In addition, Americans would probably have to reduce consumption in favor of saving in order to provide necessary investment funds for industrial productivity. While we would welcome such trends, we see nothing on the political or economic agenda to justify an assumption that they are forthcoming.

We assumed that the long-term energy price elasticity of demand in industry is only about -0.25. Some analysts have estimated long-term elasticities of -0.7 or even greater than -1.0, while others assume values ranging between -0.25 and -0.35. (ref. 21) Workers currently attempting to estimate these values on an industry-by-industry basis suggest values ranging between -0.2 and -0.4, though they warn that these values are exceedingly difficult to discern and are thus highly uncertain.[22]

Results of the "Where We Are Headed" scenario indicate that U.S. industrial energy demand will grow from 27.3 QBtu in 1985 to 38.2 QBtu in 2010 (Table III-3 and Appendix C, Table C-3). Improvement in energy intensity will be 15 percent, or 0.7 percent per year (Table III-3). This rate of energy intensity reduction results from the combined effects of price response and continuation of long-term technical trends of energy-efficiency improvement.

Table III-3. Where we are headed in industrial energy

	1985	1990	2000	2010
Energy consumption (QBtu)	27.3	29.1	33.2	38.2
Relative energy intensity per dollar of industrial output (1985 = 100)	100	96	90	85

SUMMARY

Our objective in this chapter is to estimate improvements in end-use energy efficiency that are likely between now and the year 2010 in the absence of policy shifts. We assumed that the economy will grow at 2 1/2 percent per year, that the real price of electricity will be essentially constant, and that gasoline will rise to $1.87 per gallon (in 1988 dollars). (See Appendix B for detailed assumptions.)

Our projections are summarized in Table III-4. Our estimate of the total consumption by the three end-use sectors in 2010 is 101.7 QBtu. By comparison, this total would grow to 115.4 QBtu if the energy intensities of all energy end uses were to be frozen at present levels.[23] By this measure, increased end-use efficiency is projected to reduce 2010 consumption by 13.7 QBtu, or 12 percent.

Table III-4. Where we are headed in primary energy consumption, QBtu[a]

	1988 actual	2010 Frozen efficiency	2010 Where we are headed
Buildings	29.1	42.0	39.2
Transportation	21.9	31.0	24.3
Industry	29.1	42.4	38.2
Total	80.1	115.4	101.7

[a]Electricity converted at 11,200 Btu/kWh.

A large number of factors went into the projections of continuing increases in energy efficiency. Among those that we consider particularly important are: substantial increases in fuel prices early in the next century, the emergence of a number of cost-effective industrial and transportation technologies, the near-term effect of the CAFE standards and oil price on automobiles, forthcoming implementation of federal standards applied to home appliances, and improvements to the thermal integrity of new buildings. Of these factors, the level of future world oil prices is the most uncertain and could seriously affect the estimates.

In spite of efficiency increases, the projections show a significant increase in total energy consumption by 2010. This finding is in agreement with other analyses published within the last year,[24] as shown in Table III-5.

Table III-5. Projections of primary energy consumption, QBtu

	This report	Year 2010 DOE/PE reference case	GRI baseline	DRI forecast	DOE/EIA base case
Buildings	39.2	40.6	37.2	36.4	38.5
Transportation	24.3	21.8	26.1	25.1	24.4
Industry	38.2	45.8	42.5	36.3	39.0
Total	101.7	108.2	105.8	97.8	101.9

The other analyses all used similar assumptions regarding overall economic growth and electricity prices, while GRI and DRI forecast a less rapid increase in petroleum prices.

Our results show a continuing trend toward substitution of electricity for other forms of energy as shown in Table III-6. This trend, which is driven partly by technological developments and partly by the projections of relative price changes, is also expected in the other recent studies.

Table III-6. Where we are headed in primary energy consumption by end-use fuel type

	1988 actual		2010	
	QBtu	Percent	QBtu	Percent
Electricity	28.6	35	46.7	46
Petroleum	32.7	41	35.3	35
Natural gas	15.8	20	14.9	15
Coal/other	3.0	4	4.4	4
Total	80.1	100	101.3	100

It should be noted that the scope of the study excluded efficiency increases in the electric utility sector. Thus, conversion of electrical demand to thermal units was held constant in future years at 11,200 Btu/kWh, the 1988 value. In this respect we have neglected important sources of additional energy efficiency.

IV. COST-EFFECTIVE EFFICIENCY

The scenario of the previous chapter considered a continuation of previous trends. It is well known that these trends fail to take advantage of many cost-effective opportunities for increasing energy efficiency. In this chapter we ask how much additional efficiency, beyond what we expect to occur, could be achieved without additional cost to consumers.

In this scenario we assume that decisions about equipment selection and choices concerning energy-saving designs in buildings are determined by life-cycle economic considerations. Purchasers are modeled as if they consider first cost plus the sum of life-cycle operating expenses, discounted at 7 percent real. Those investments (in more efficient processes, equipment, or buildings) which have the minimum life-cycle costs are made in preference to other designs. The 7 percent discount rate was selected to approximate socially optimal decisions, although, as discussed in Chapter V, consumers often appear to use much higher discount rates. The calculations exclude the costs of obtaining information, the financial risks associated with purchasing new technologies, and other transaction costs.

The cost-effective scenario assumes the same fuel prices, population, and economic conditions as in the previous, "Where We Are Headed," scenario. It is again assumed that new technologies will be introduced gradually, following completion of research and development, and it is assumed that equipment replacements will be made when economical. Obviously, many decision factors would have to change for the country to move toward a cost-effective scenario; these factors are discussed in Chapter V.

A large data base of technological improvements already commercially available provides much of the basis for characterizing the alternative future. We assume that R&D will continue on new technologies to bring them into the marketplace, but do not postulate major breakthroughs. A number of important innovations which are expected to be introduced before 2010 are not mentioned because we estimate that their impact will be mainly in later years.

BUILDINGS

Cost-effective efficiency measures are defined as those whose incremental life-cycle cost is less than the cost of energy they save. The cost of conserved energy (CCE)[1] can be displayed in a series of "conservation supply curves" as illustrated in Appendix C, Fig. C-1 and Table C-9, for residential electricity in the year 2000; and in Fig. C-2 and Table C-10 for residential gas in the year 2000. In the example for gas the least expensive option was installation of high-efficiency gas dishwashers with a CCE of 1.39 $/MBtu (well below the expected cost of gas), while the largest energy saving could be obtained with installation of an efficient gas heating system at a CCE of 3.67 $/MBtu. Such conservation supply curves were constructed for each fuel, year, and sub-sector. These curves include consideration of turnover of equipment and buildings in the year illustrated, so that projected energy savings are limited to the purchases of equipment and retrofits projected to occur in that year. The energy savings displayed are from measures implemented in the year 2000, not the cumulative savings accruing in that year due to measures implemented up until that time. The cumulative savings are captured in Table C-4, Appendix C. Substitution of HCFCs for CFCs in residential refrigerators and freezers was accounted for, but effects of such a substitution were not estimated for residential air conditioning or commercial applications.

Overall, in the residential sector the largest savings are projected for more efficient refrigerators. The design changes include more efficient compressors and fans, and significantly increased vacuum insulation. Important savings projected by retrofit measures to existing buildings include additional wall and ceiling insulation and improved building equipment. However, retrofit potential is certainly underestimated in the simple methodology employed here. Improvements to lighting may also yield substantial savings, but these were not estimated for either the residential or commercial sectors because of modeling limitations. (See Table C-11, Appendix C, for additional details.)

In the commercial sector the biggest absolute reduction in energy consumption occurs for adjustable-speed fan motors. Several technologies can be used to improve the efficiency of a motor when less than its full capacity is required. One technology, the electronic variable-speed drive, adjusts the speed of motors by electronically varying the input voltage and frequency to the motor. These drives can reduce energy consumption in systems with varying loads, including fans in variable air volume systems,[2] water pumping, and air-conditioning chillers. Cogeneration savings were omitted because of model limitations.

Over 50 QBtu of cumulative energy savings (from 1990 through 2010), worth more than $300 billion, are projected for the combined building sector (residential and commercial) from the 29 efficiency measures analyzed, all at costs below the projected cost of supplying energy. In 2010 projected energy savings amount to 14 percent of the annual energy consumption projected for buildings in the previous chapter. These technologies would save even more energy beyond 2010, once they are in place. Furthermore, additional savings are potentially available if faster turnover of existing equipment were considered.

Table IV-1 and Appendix C, Table C-4 summarize the results of the "Cost-Effective Efficiency" scenario.

Table IV-1. Cost-effective efficiency in buildings energy

	1985	1990	2000	2010
Energy consumption (QBtu)				
Residential	16.0	17.2	16.4	17.7
Commercial	10.8	13.1	14.8	16.1
Total	26.8	30.3	31.2	33.8
Energy intensity				
Residential (MBtu/household)		180	148	140
Commercial (kBtu/ft^2)		206	190	172

In the residential sector, energy growth from 1990 to 2010 is reduced to 0.2 percent per year. Residential energy intensity declines from 180 million Btu per household in 1990 to 140 million

Btu per household in 2010. The trend toward electrification is increased. In the commercial sector, energy growth is reduced to 1.0 percent per year, and energy intensity declines from 206 thousand Btu per square foot in 1990 to 172 thousand Btu per square foot in 2010. Overall growth in primary energy consumption in buildings (residential and commercial combined) is reduced to 0.6 percent per year.

The results of the "Cost-Effective Efficiency" scenario were also analyzed to separate residential energy savings into three components: new shell measures, retrofit shell measures, and equipment measures. New shell measures are thermal integrity improvements to new buildings. Retrofit measures are thermal integrity measures applied to buildings already in place in 1980, including ceiling insulation, wall insulation, floor insulation, windows, and infiltration. Equipment measures are efficiency improvements in appliances and heating and cooling equipment beyond those attributable to existing national standards. The analysis showed 7 percent of the cumulative savings through 2010 to be from new shell measures, 23 percent from retrofit, and 70 percent from equipment. (This is an underestimate of retrofit potential, since only those houses in place by 1980 are considered candidates for retrofit, and many of them undertake simple retrofits prior to 1990 and are not subsequently upgraded.)

Commercial sector savings were similarly separated into new buildings and retrofits, with equipment measures contained in both. The result for the year 2010 was that annual savings from retrofit were 47 percent and savings from new buildings were 53 percent of the total. Equipment measures were included in savings attributable to new and retrofit buildings.

Economic impacts of this scenario for the residential sector, compared to the "Where We Are Headed" scenario, are that in 2010 households will pay an additional $5 billion (1987 dollars) for efficiency measures, and will realize a savings of $21 billion in reduced energy bills in the same year.

TRANSPORTATION

Within the fleet of new vehicles produced each year, there is a wide range of technological sophistication. For example, in light-duty vehicles in 1989 it was possible to buy a vehicle with a 5-liter, 140-horsepower engine using a 2-barrel carburetor, with 8 cylinders and 2 pushrod valves per cylinder; or alternatively, a vehicle with a 1.6-liter, 145-horsepower engine using fuel injection, with 4 cylinders, a supercharger, an intercooler, and 4 double-overhead-cam valves per cylinder. For the 1990 model year it will be possible to buy a sports car with a turbocharged *and* supercharged 4-valve, 2-liter engine with 230 horsepower. In terms of horsepower per liter of engine displacement, this represents a very wide variation from 28 to 115.[3]

Many technological options now introduced in at least part of the new vehicle market can be used to improve future fuel efficiency. These technologies include overhead camshafts, roller cam followers, friction-reducing cylinder materials, ceramics to reduce heat rejection, compression ratio increases through more sophisticated electronic controls and better combustion chamber design, multi-point fuel injection, more valves per cylinder, turbocharging, supercharging, intercooling, electronic transmission control, four- and five-speed automatic transmissions, torque converter lock-ups, continuously variable transmissions, front-wheel drive, better aerodynamics, and improved accessory designs. Excluding weight reduction, estimates by DiFiglio, Duleep and Greene imply that a 32 percent fuel economy gain could be obtained by increasing the penetration of technologies which are now in less than 50 percent of new cars.[4] The net opportunity by the year 2000, however, is less than 32 percent, both because some cars already will have these features and because of onomic scheduling of introduction of the new technologies. We have calculated an approximately : -percent efficiency gain through substitution (at constant horsepower) of a turbocharged, tercooled, double overhead camshaft, four valve per cylinder, multi-point fuel injected engine ›upled to a four-speed lock-up transmission or a conventional throttle body fuel injected, two valve :r cylinder engine coupled to a three-speed automatic transmission without a lock-up torque ›nverter. This shift does not include all of the technologies on the DiFiglio, Duleep and Greene ;t but includes two that they do not—turbocharging and intercooling. On the whole, this estimate thus not as optimistic as the DiFiglio, Duleep and Greene estimate, but the two are similar. A vo-stroke engine for smaller cars is another possibility. Although it has environmental problems, ıere is optimism that these problems can be overcome.

›iFiglio, Duleep and Greene estimate that average new car fuel economy will reach 34.3 mpg by he year 2000. However, they estimate that the cost-effective level of fuel economy in the year .000 is 36.4 mpg, assuming that consumers drive an average amount, use a 10 percent discount ate and evaluate the vehicle over a 10-year lifetime, using $1.32 gasoline. Our scenario calls for ;1.43 gasoline in the year 2000. We assume a 7 percent discount rate in this study and have higher ›ase gasoline prices by the year 2000 than used by DiFiglio, Duleep and Greene. Thus we selected ι value of 38.5 mpg in 2000 as the cost-effective value to be achieved in our Cost-Effective Efficiency scenario. This is just below the "maximum technology" value of 39.4 mpg estimated by DiFiglio, Duleep and Greene, a value which defines the realistic technology limits for the year 2000.

The same patterns can be found in other vehicle types. The most advanced new jet aircraft are far more efficient than older aircraft in service. On a 1,000-mile trip, aircraft produced in the 1960s are capable of between 40 and 50 seat-miles per gallon, while the new Boeing 757 and 767 now in service have a fuel efficiency of 70 seat-miles per gallon. Improvements now being introduced arise from a combination of higher bypass ratio engines, increased compressor and turbine efficiencies, and more energy-efficient flight planning and operations. Further opportunities for fuel efficiency could be obtained by use of fanjets. Such an aircraft is the Boeing 7J7, which is in testing but not now in production. It may achieve 130 to 150 seat-miles per gallon. Like automobiles, aircraft can also benefit from weight reduction and better aerodynamics. Use of composite materials for weight reduction and laminar flow in airframe and wing design will contribute to future gains.

Table IV-2 summarizes the results of our Cost-Effective Efficiency scenario. Additional details are given in Appendix C, Table C-5.

Our assumptions lead to a Cost-Effective Efficiency scenario in which automobile and light truck fuel economy rise 10.9 and 6.6 mpg higher by 2010 than our "Where We Are Headed" scenario. The energy consumption of light-duty personal vehicles declines steadily, even in the 1990s.

INDUSTRY

In this section we estimate the contribution of the industrial sector if this sector were to use energy with cost-effective efficiency improvements. This projection differs from the "Where We Are Headed" case only by the assumptions we make for rates of energy-efficiency improvement. We set these rates equal to levels which, based on our review of the literature, we believe would capture most of the cost-effective potential for energy savings. We also illustrate specific energy-efficiency investment opportunities in order to justify our use of these energy-efficiency improvement rates.

Table IV-2. Cost-effective efficiency in transportation energy

	1985	1990	2000	2010
Energy consumption (QBtu)				
Personal travel	9.2	9.9	7.8	6.8
Freight	6.2	6.9	7.4	8.6
Air travel	1.7	1.9	2.0	2.1
Other transportation	3.0	3.0	2.8	2.7
Total	20.1	21.7	20.0	20.2
Energy efficiency				
Automobile (including fleet autos) (mpg)	18.2	19.4	28.6	37.5
Personal light trucks (mpg)	14.5	15.5	20.8	26.3
Freight (ton-miles/kBtu)	0.68	0.68	0.76	0.81
Air travel (passenger-miles/kBtu)	0.16	0.18	0.24	0.31

The rates we applied for energy-efficiency improvement were derived from six major studies (see Table C-12).[5] The rates of energy-efficiency improvement indicated by these six studies are technically possible and economically justifiable, though not likely to take place without major new stimuli such as price shocks or policy changes. We use the most favorable sectoral efficiency rates suggested in the six major studies cited.[5] This decision reflects our purpose of estimating the maximum industrial energy-efficiency potential, as opposed to trying to simulate how consumers will actually behave. This potential was based on three factors: the investment cost of various energy-efficiency opportunities, the extent of their applicability, and the rates of capital improvement and replacement which can be achieved.

The method by which we introduced this potential in the model was to increase the assumed values for energy-efficiency improvement—annual rates of sector-specific energy-intensity reduction per unit of output—to the highest levels estimated by any of the six studies. For example, the SERI study suggested that the rate of decrease in energy intensity of the chemicals industry could be as great as 2 percent per year. Our "Where We Are Headed" scenario result for this subsector suggested that price response would generate an annual 1 percent end-use energy-intensity decline. In the "Cost-Effective Efficiency" case, therefore, we increased the technical efficiency parameter for that sector by the difference—an additional 1 percent decline per year. Note that this resulting 2 percent rate of decline—the energy-efficiency improvement rate—does not include structural change, which is estimated separately in the model and adds about 0.5 percent per year energy-intensity reduction for industry overall.

It is worth reiterating that the choice of the highest rate indicated for an individual sector by one of the six studies is justified on the basis of the objective of our study: to see how far we can go in energy efficiency. We have simply chosen the largest estimate of efficiency potential that is also credible.

We found evidence that significant efficiency potential does indeed exist. For example, opportunities for cutting energy requirements per ton of steel exist throughout the steelmaking process in both the United States and Japan.[6] The electric arc furnace, for example, uses virtually 100 percent scrap and requires only about 10 MBtu per ton of steel produced. Only 36 percent of U.S. steel is made with this furnace, and this could probably be increased to 60 percent.[7] The recycling rate is of course constrained to substantially less than 100 percent because impurities—which cannot be cost-effectively removed given current technology—unacceptably alter the quality of recycled steel beyond a given point. Similarly, energy use in making iron and steel from virgin ore could be cut dramatically by direct reduction or smelting of ores. Even greater energy savings, as much as 6 MBtu per ton, could be achieved by developing and implementing near net-shape casting.[8] Some of these options are not cost effective, and those which are may not be additive. Direct reduction, for example, would probably require high-cost natural gas, and 100 percent recycling is not possible. Nevertheless, we find that existing technology in cokemaking, blast furnace operation, steelmaking, and casting could, by 2010, save up to 42 percent of the total energy required to make steel, and at a cost below that of energy supply. Achieving this potential would permit a 2.4 percent rate of energy-efficiency improvement over the period 1988 to 2010. For comparison, a 1.5 percent rate of improvement would merely bring the U.S. down to the current level (not the year 2010 level) of Japanese energy efficiency in steelmaking.[9] (See Appendix C, Table C-13 for illustrations of efficiency investments in this sector.)

Similar examples can be found in aluminum production. Significant opportunities exist, for example, in improved design of electrolytic reduction cells, better electrodes in these cells, direct casting, and recycling. We estimate that cost-effective measures (cheaper than energy supply) in aluminum processing could reduce total energy requirements per ton by 36 percent by 2010. This estimate excludes certain large opportunities for additional improvement. For example, commercialization of processes such as carbothermic reduction of alumina is not considered likely in the United States over the next 20 years, partly because new aluminum production capacity is expected to be constructed offshore.[10] (See Appendix C, Table C-14 for illustrations of efficiency investments in this sector.)

The chemical industry is vastly more complex than primary metals and cannot be assessed straightforwardly for energy-efficiency potential. Instead, a few efficiency opportunities in both chemical processes and generic energy uses—distilling, separation—can be illustrated.

Examples of process changes include the new Unipol process for making polyethylene, which uses only 35 percent as much energy per pound of output as conventional processes. Similarly, a low-pressure oxidation process—LP-OXO—cuts energy requirements per pound of industrial solvent or plasticizer by 40 percent. These two examples are now used in 25 and 50 percent of world production, respectively.[11]

About half of all energy used in the chemical industry is for steam and power and process heat, which are used principally for distillation, separation, and pumping. Machine drive accounts for about 10 percent, and electrolysis accounts for about 3 percent. Fuels used as feedstocks account for most of the rest. Thus it is useful to assess the generic potential for reducing energy use common in thermal and mechanical processes in chemicals production. Opportunities include upgrading electric motor efficiency, cogeneration, thermal recompression in evaporation, and automated process control.[12] (See Appendix C, Table C-15 for illustrations of efficiency investments in this sector.)

In the paper industry, promising technologies include continuous digesters, oxygen bleaching, upgraded evaporators, mechanical dewatering, boiler efficiency improvement, increased biomass use, and cogeneration. Various studies estimate that specific energy intensity in this industry could be reduced by one-third to two-fifths by 2010.[13] Paper drying has been estimated to be the single largest energy-consuming operation in the production of pulp and paper board. Technical opportunities for efficiency improvement include impulse drying, superheated steam drying with exhaust recompression, improved dewatering of sheet before drying (wet pressing), and modern well-insulated drying enclosures (air recovery hoods). However, while new "greenfield" mills can incorporate the latest process technologies when they are built, the capital cost of introducing new energy-saving technologies into existing mills can be prohibitive. The energy savings associated with any given process technology is also quite site specific. Recycling of paper is thought to offer greater opportunity for energy-intensity reduction, although this practice is considered to be dependent on public policies and market development of recycled products. Continued increase in the use of waste fuel is expected in the paper industry.[14] Finally, increased application of computer control systems, coupled with process sensor development, is anticipated.[15]

Petroleum refining has the potential for cost-effective efficiency improvements through improved process control, cogeneration, electric motors, and heat recovery. It is plausible that 15 to 20 percent of energy used in petroleum distillation could be saved by the year 2010. However, the most recent independent study available to us for this sector was published in 1983.[16]

In cement making, the inefficient wet process still accounts for almost one-third of production, though the dry process uses 26 percent less energy per ton.[17] One hundred percent penetration for the dry process by 2010, complete with heat recovery and optimum efficiency opportunities including more efficient motors for grinding, could reduce the energy required for cement making at least 20 percent. Other opportunities in stone, clay, and glass processing include replacing inefficient motors used in grinding and polishing, and upgrading inefficient furnaces used in glass melting.[18]

The balance of the industrial sector (not included in the first five subsectors listed in Appendix C, Table C-7) requires about one-third of the total industrial energy demand (Appendix C, Table C-7). It is difficult to generalize about the potential for improvements in these industries, though generalized industrial energy-efficiency cost curves have been constructed for at least one region.[19] It is not possible at this time to construct a proper "energy-efficiency supply curve" for the industrial sector as a whole. However, work sponsored by the U.S. Environmental Protection Agency, and just beginning at Pacific Northwest Laboratories, will specifically attempt to construct such a curve.[20]

The utilization of cost-effective energy-efficiency opportunities will depend heavily on the rate of replacement or upgrading of existing industrial plant and equipment. This rate is not the same for all industries, as illustrated by the fact that the average age of the U.S. paper industry's plant and equipment is estimated to be on the order of 20 years, while that of the chemical industry is probably half that.[21] The aforementioned studies, fortunately, explicitly included this factor in their estimates. For example, SERI[22] made projections of the future shares of new plant and equipment, estimated the future energy intensity of existing and new equipment, and weighted future energy intensities on the basis of future share of new and old equipment.

Our "Cost-Effective Efficiency" scenario (Table IV-3 and Appendix C, Table C-6) requires about 34 QBtu in 2010, 11 percent less energy than the "Where We Are Headed" case. Most of the difference in demand between the scenarios occurs in oil and gas consumption. (See Appendix C, Tables C-3 and C-6). The annual energy efficiency improvement rates of the "Where We Are Headed" and "Cost-Effective Efficiency" scenarios average 0.7 percent per year and 1.1 percent per year respectively (see Tables III-3 and IV-3).

Table IV-3. Cost-effective efficiency in industrial energy

	1985	1990	2000	2010
Energy consumption (QBtu)	27.3	28.3	30.5	33.9
Energy intensity per dollar of industrial output (1985 = 100)	100	93	83	76

As a sensitivity test, we applied the efficiency improvement potential estimated by Goldemberg et al. with structural change rates also suggested in that study.[23] That is, we ran the model assuming energy efficiency increases at 2 percent per year and industrial output grows at eight-tenths the rate of GNP. We implemented these assumptions by using the model simply as an accounting device—setting price change to zero, the technical efficiency parameters to -0.02 and the structural change parameters all to 0.8 times GNP growth. The result of this scenario was year 2010 energy demand of 29.2 QBtu, some 4.7 QBtu below our "Cost-Effective Efficiency" scenario.

We also tested the sensitivity of our results to price assumptions. We set price changes for oil, gas, coal, and electricity equal to an annual 1 percent rate of increase. The result of this test was energy demand in 2010 of 37.0 QBtu, an increase over our "Where We Are Headed" scenario of 3.1 QBtu. Energy demand was shifted significantly among the energy carriers, with much lower consumption projected for electricity and much higher use of oil and gas.

SUMMARY

In this chapter we have estimated the reduction in energy demand that would occur through cost-effective efficiency opportunities. Table IV-4 summarizes these estimates and compares them with the results obtained in Chapter III.

Table IV-4. Cost-effective energy efficiency

Year 2010 primary energy consumption (QBtu)

	Frozen efficiency	Where we are headed	Cost-effective efficiency
Buildings	42.0	39.2	33.8
Transportation	31.0	24.3	20.2
Industry	42.4	38.2	33.9
Total	115.4	101.7	87.9

The calculations indicate that the capture of most opportunities for cost-effective efficiency would reduce 2010 energy consumption by 28 QBtu compared to frozen efficiencies and by 14 QBtu compared with our projection of the most probable outcome. The buildings sector would provide 41 percent of the latter reduction, industry 33 percent, and transportation 26 percent. Most of the potential gains in transportation are projected to occur through market forces, while this is not true for the other two sectors.

Projections by fuel type are given in Table IV-5. As in the previous scenario, there is a substantial increase in the fraction of total energy supplied by electricity compared to 1988. The quantity of petroleum projected for 2010 decreases from today's level. There may be a question as to whether certain of these results are consistent with our assumption that oil prices will rise rapidly.

Table IV-5. Cost-effective primary energy consumption by end-use fuel type

	1988 actual		2010	
	QBtu	Percent	QBtu	Percent
Electricity	28.6	35	42.8	48
Petroleum	32.7	41	27.9	32
Natural gas	15.8	20	14.0	16
Coal/other	3.0	4	3.2	4
Total	80.1	100	87.9	100

Our estimates of how far we can go in energy efficiency are subject to a number of uncertainties. Future fuel prices are certainly a primary determinant of energy demand. International oil prices have been volatile in recent years and may again exhibit unpredictable gyrations. A further limitation in our study is that we were unable to account for the effect of reduced energy demand on energy prices. Increasing concern over environmental impacts, such a global warming, could also introduce major changes in energy use. Restrictions on carbon dioxide emissions would increase the cost of fossil fuels and electricity, and thus accelerate the adoption of efficient energy systems. Furthermore, our models failed to include some significant technologies for increasing end-use energy efficiency. Some examples are pointed out in earlier sections of this chapter.

The range of uncertainty is illustrated by other published studies on energy conservation. Some of these were analyzed by Carl and Sheer,[24] who normalized the results to a common projection period of 1980 to 2000. The six studies they normalized show an average conservation potential of 18.4 QBtu in 2000, with individual studies ranging from 8.8 QBtu to 25.7 QBtu. (ref. 25) For comparison, the present study yields a difference of 13.8 QBtu between the two scenarios. However, the degree of comparability is not clear. As Carl and Sheer note, "The purposes as to why each of the studies was conducted were substantially different. Differences in purpose could not be normalized when comparing the estimates of conservation potential across the studies."[26] In another recent study, Goldemberg et al.[27] suggest that end-use efficiency plus large efficiency gains by electric utilities could reduce total U.S. consumption to 52.6 QBtu by 2020.

The differences among these estimates also reflect conceptual difficulties in determining how far we can go in energy efficiency. First, the definition of the potential (for example, the discount rate) varied among studies. A second problem is that life-cycle cost as a function of efficiency has a flat, broad minimum for many energy uses, making it impossible to determine the optimum accurately. Third, there is a lack of agreement on the cost and desirability of measures to induce efficiency improvements. Thus strategies that were included by the authors of some of the studies were rejected by others as impractical or a reduction in living standards.

A recent study published by the American Council for an Energy-Efficient Economy[28] proposed a national goal of 2 1/2 percent per year reduction in E/GNP through improvements in end-use efficiency. In terms of our results, this goal would mean holding energy consumption constant at 80 QBtu through 2010. Our results, though less optimistic, do not necessarily mean that goal is not achievable. In fact, goal setting itself can motivate researchers and corporations to find cheaper ways of meeting objectives. For example, assessments of the economic effects of replacing CFCs in order to protect the global ozone layer have gone in a few short years from unacceptably high to moderate or zero.[29]

V. CLOSING THE EFFICIENCY GAP: BARRIERS TO IMPROVING ENERGY EFFICIENCY

"If we don't change our direction, we are liable to end up where we're headed."

-Anonymous

The projections developed in the preceding chapters demonstrate the disparity between the large potentials in all economic sectors and the energy-efficiency actions likely to be taken during the next two decades. Closing this efficiency gap is important because of the environmental, economic competitiveness, and national security benefits that would result. The constraint on efficiency improvements in the short term is not primarily technological. *The primary barrier is insufficient implementation of existing cost-effective technologies.* Pursuit of additional opportunities through research, development, and demonstration is important in the long run (see Chapter VI), but significant efficiency improvements are technologically and economically feasible today.

This chapter identifies and discusses briefly the major barriers to improved energy efficiency, the obstacles that stand between present trends and future opportunities. Although these barriers occur in the research and development, production, commercialization, acquisition, and use of energy-efficient systems, this chapter focuses on those related to acquisition and use (Table V-1) because little information is available on the upstream barriers. See Blumstein et al.,[1] Hirst,[2] and Fisher and Rothkopf[3] for further discussions of the barriers described here. Although many studies have examined individual barriers and a few, such as the three cited above, have reviewed information on several barriers, none determined which are the most important and which are most amenable to remedy.

Table V-1. Barriers to improving energy efficiency in the United States

Structural barriers: conditions that are beyond the control of the individual

- Distortions in fuel prices
- Uncertainty about future fuel prices
- Limited access to capital
- Government fiscal and regulatory policies
- Codes and standards
- Supply infrastructure limitations

Behavioral barriers: problems that characterize the end-user's decision making

- Attitudes toward energy efficiency
- Perceived riskiness of energy-efficiency investments
- Information gaps
- Misplaced incentives

Numerous policy options are available for addressing the barriers discussed in this chapter. However, analysis of these options does not fall within the purview of this report.

DISTORTIONS IN FUEL PRICES

The prices that consumers pay for fuels do not reflect fully all the environmental and social costs associated with fuels production, conversion, transportation, and use. For example, the costs of acid rain and of global warming (CO_2 emissions) are not now reflected in the prices of fossil fuels and electricity. Similarly, the national security and foreign balance-of-payments implications of oil imports[3] are not incorporated in fuel oil and gasoline prices. At present it is not possible to estimate the costs of such externalities, but fuel prices would rise significantly if they were to reflect their full social costs. And with much higher fuel prices, investments in energy-efficient technologies would be more cost effective.

The situation is further complicated for electricity because of the way that state public utility commissions set electricity prices. Traditionally, prices are set so that they reflect the average cost of producing electricity.[4] If, however, the costs to build and operate future power plants are greater than the current average, then consumers face inappropriate price signals. A similar, although less dramatic, situation occurs for natural gas.

The extent to which increases in fuel prices caused by efforts to internalize environmental and social costs would decrease fuel use is uncertain. Bohi and Zimmerman, in their review of econometric studies of energy demand,[5] note that "Outside of residential demand for electricity, the quality of the information obtained from years of study ranges from weak to very poor. Information on commercial and industrial demand is weakest... ." Thus, it is hard to estimate accurately the effects of higher fuel prices on energy-related purchase and operations decisions. Overall, however, price signals can strongly motivate, or inhibit, energy end-use efficiency.

UNCERTAINTY ABOUT FUTURE FUEL PRICES

The prices paid for all fuels, especially crude oil, fluctuated dramatically over the past 15 to 20 years,[6] leading to perceptions of uncertainty about future prices. The price of crude oil was almost 400 percent higher in 1981 than it had been 9 years earlier. Then crude oil prices dropped precipitously and today are back to their 1974 level (in real terms). Even electricity prices, which showed the least volatility of all fuel prices, changed substantially during this period, rising during the 1970s and then falling again. Future fuel prices are even more uncertain than implied by the volatility of past prices, because of the likelihood that environmental controls will increase. Acid rain legislation is likely to increase the cost of producing electricity at coal-fired power plants, and concerns about global warming may have even more far reaching effects on the future availability and cost of fossil fuels.

Fuel-efficiency improvements in transportation are largely dependent on fuel price. Perception of future oil price and satisfaction with the choice of vehicle are interrelated. For example, a large number of diesel car buyers were dissatisfied with their vehicles because of the fuel price collapse after 1983.[7]

How are consumers to make rational choices about the purchase of new energy-using systems such as cars, heating equipment, new buildings, and motors when the basis for estimating long-term operating costs is so uncertain? Absent guidance on the future course of fuel prices, decision makers may avoid energy-efficient systems because of their higher initial costs.

LIMITED ACCESS TO CAPITAL

Energy-efficient systems are generally more expensive than their less-efficient counterparts. Obtaining the additional money to pay the incremental capital costs of efficiency improvements is often a problem. Obviously, money is a major barrier for low-income households and cash-constrained industries. Many studies found very high implicit discount rates associated with residential investments in efficient refrigerators, air conditioners, other appliances, space heating equipment, automobiles, and retrofit measures, ranging up to 100 percent.[8]

Industry theoretically is rational in responding to prices and should be price-sensitive. Yet abundant evidence suggests that industry discriminates between market-share and energy-efficiency (cost-saving) investments, allocating capital to the former in preference to the latter. In fact, industry typically requires paybacks of two years or less for cost-saving investments.[9] This factor can be attributed only partially to management's short-term time horizons because industry does make market-share investments with longer payback periods. The issue is a complex one of industrial organization and remains a prime area for research.

GOVERNMENT FISCAL AND REGULATORY POLICIES

Traditionally, the federal government has provided greater support for energy production than for energy efficiency, in terms of both tax policies and support for research and development. Heede, Morgan, and Ridley,[10] for example, estimated that the Federal Government provided subsidies to energy-supply industries of more than $40 billion in 1984, primarily through federal tax breaks. Tax subsidies to energy-efficiency industries have been minimal, in comparison. Support for research and development has greatly favored supply options. Fulkerson et al. calculated that only 7 percent of the Federal Government's FY 1988 energy research and development budget ($156 million) was allocated to energy efficiency.[11]

Similar disparities occur with respect to state regulation of electricity. Wiel noted that traditional rate regulation implicitly encourages utilities to increase electricity consumption between rate cases.[12] Such sales increases translate directly to greater earnings for utility shareholders. Wiel[12] and Moskovitz[13] suggest modifications to traditional rate-of-return regulation, which would reward utilities for implementing cost-effective energy-efficiency programs.

Thus a variety of government policies, practices, and programs strongly affect private decisions on the purchase and operation of energy-using systems. Unfortunately, these government actions tend to favor increased energy use rather than greater energy efficiency.[14]

CODES AND STANDARDS

Codes and standards are usually viewed as instruments of change and not as barriers. For instance, the federal fuel economy standards had a substantial effect on raising new car economy from 17 mpg in 1976 to 28 mpg in 1989.[15] Appliance standards in California have raised the efficiency of major home appliances, and the voluntary standards developed by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers have improved the thermal performance of residential and commercial buildings by creating nationally recognized guidelines for their design and construction.

In spite of these positive influences, the process of setting and revising standards and codes is often slow, cumbersome, and dominated by special interests. Because codes and regulations take a long time to adopt and modify, they sometimes specify obsolete technologies, thereby inhibiting innovation.[16] For building codes, the dominance of local interests helps explain why there are several thousand different code specifications. These code variations fragment the market and contribute to manufacturing inefficiencies.[17]

Codes and standards covering materials and equipment can be used to encourage the implementation of energy-efficiency options. However, standards are mostly concerned with health, safety, and reliability rather than with energy efficiency.

SUPPLY INFRASTRUCTURE LIMITATIONS

The availability of new energy-conserving technologies is often limited to particular geographic regions of the country. For example, compact fluorescent lamps are generally available only in those areas where electric-utility programs promote these products. The markets for heat-pump water heaters and ground-coupled heat pumps illustrate the consequences of limited supply infrastructures.[18] These supply limitations make it difficult for consumers to satisfy their demand for energy-efficient technologies.

Alternative fuels for the transportation sector suffer from lack of infrastructure. The corrosive properties of methanol require substantial investment in its transportation, distribution, and storage. The use of CNG would entail construction of still another new distribution system. Limiting these alternative fuels to selected geographic areas may cause rejection by consumers.

There is similarly a lack of people skilled in engineering, operations, and maintenance to adequately nurture the development and deployment of new energy technologies. Energy issues are not strong components of the college curricula that train automotive, industrial, and HVAC engineers. In addition, companies that manufacture, distribute, and service energy-efficient products underinvest in training programs to keep their employees abreast of the latest technological advances. For example, the reliability and performance of electric heat pumps suffered greatly during the 1950s and 1960s because installers and technicians were not adequately trained.

The infant industry of energy service companies is another weak link in the delivery of energy-efficient technologies to end users. With the exception of a few large companies, the industry is composed primarily of small firms that lack the resources and name recognition to market their services effectively.

ATTITUDES TOWARD ENERGY EFFICIENCY

Throughout most of the 1980s, Americans lost interest in saving energy as fuel prices dropped and supplies appeared to be plentiful. For example, fuel economy was rated the most important attribute in selecting a new car in 1980. In January 1985, fuel economy had dropped to fifth place behind dependability, price, safety, and quality of workmanship.[19] By the end of 1985 it had dropped to eighth.[20]

Recent concerns about environmental quality seem to have changed public attitudes towards energy efficiency. Public opinion polls show that Americans are deeply concerned about environmental issues, recognize the strong links between environmental quality and energy production, and therefore favor energy efficiency over increased energy production by substantial margins.[21,22] At the same time, the public places a high premium on comfort, ease, and convenience, goals that may appear to conflict with energy efficiency. Thus, it is unclear whether the positive attitudes that Americans have for improving energy efficiency will be reflected in their energy-related purchase and operation decisions.

PERCEIVED RISKINESS OF ENERGY-EFFICIENCY INVESTMENTS

To many, investing in new energy-efficient systems is risky. They know what the capital cost is for such systems but are uncertain about the long-term savings in operating costs. Perhaps more important, they are unsure whether installing new equipment will disrupt ongoing operations and whether this new equipment will increase downtime or reduce productivity during operation. For example, consumers bought diesel-powered cars at premium prices following the 1979 fuel price rise. Manufacturers rushed to satisfy this demand without conducting enough tests on the new product. The poor performance of these vehicles created a mistrust of unknown vehicle technology among consumers.

A project conducted for the Electric Power Research Institute found that such concerns were very important to decision makers in the commercial sector.[23] Risk aversion was found to be a key element affecting customer participation in utility demand-side management programs, more important than economics. Another EPRI project found that the most important factor affecting commercial-sector participation was risk management followed by economics, quality, and capital budget constraints.[24]

INFORMATION GAPS

Credible information on the performance of energy-efficient technologies is often lacking. Such information is critical to those who decide on the commercial deployment and market penetration of new technologies, including investors, regulators, consumers, and others.

A recent survey of industry leaders identified the need for federally supported demonstrations of energy-efficient technologies.[25] Information regarding the technical and economic viability of such technologies under full-scale, actual usage conditions is often scarce. The absence of such data leads to greater perceived risks and a reluctance to adopt such systems.

Aggravating this situation is the fact that energy use is largely invisible and automatic. Consumers have no way of knowing from their monthly utility bills how much energy is used for different pieces of equipment. This lack of information on energy use by end use complicates decisions on energy-efficiency improvements. Transportation energy, also, is consumed and paid for in bits and pieces. The consumer often does not know the full annual cost.

Some information on the energy efficiency of products is well understood, such as the mpg rating on vehicles. Others, however, are not. Evidence of this is provided by a recent study of gas furnace purchases by Cantor and Trumble,[26] which found that the energy-efficiency rating is a poorly understood characteristic of furnaces. The importance of this information gap is provided by studies that have shown that households will reduce their energy consumption when provided with detailed information feedback on the energy consumed by their appliances, heating equipment, and air conditioners.[27] Farhar and Fitzpatrick[28] conclude that "the bulk of the literature provides evidence that information feedback can play a role in reducing electricity consumption, on the order of from 5 to 20 percent."

Home energy audit programs have attempted to narrow this information gap, but have been much less effective than they could be, partly because information is presented in a dry, statistical fashion.[29] Making energy audits vivid and personalized (e.g., having the auditor caulk one window or having the householder help conduct the audit) would encourage household adoption of recommended measures. Influence is also greater, the more concrete and specific the audit recommendations and the clearer the path to be taken.

MISPLACED INCENTIVES

Consumers often must use the energy technologies selected by others. Industrial buyers select the technologies that are used in the production process. Specialists write product specifications for military purchases that limit access to alternatives. Architects, engineers, and builders, without direction from the ultimate owners and occupants, typically decide the energy efficiency of buildings and their equipment. Builders select and purchase large numbers of furnaces, water heaters, and other appliances for new homes. Used-vehicle buyers must choose from those vehicles purchased by generally more affluent, new-vehicle purchasers who may have placed a low value on fuel efficiency.

The involvement of intermediaries in the purchase of energy technologies leads to an emphasis on first cost rather than life-cycle cost. In the buildings sector, technologies are selected primarily to stay within a construction budget. This is a deterrent to the use of energy-efficient technologies, which have higher first costs but lower life-cycle costs than conventional technologies. Incentives to reduce life-cycle costs are usually relevant only to those who pay the energy bills (tenants or owner-occupants). These "imposed choices" limit or eliminate the ultimate consumer's role in decision making.[30]

DISCUSSION

As discussed above, a variety of obstacles prevent energy users from adopting cost-effective energy-efficiency practices and measures. These barriers are important because energy use has substantial social effects, as noted in Chapter II. Unfortunately, we are unable to explicitly identify which barriers are the most important obstacles to improved energy efficiency and the kinds of actions that could overcome these barriers. Although numerous attempts have been made to identify barriers, none of the studies has reliably ranked the barriers by importance as obstacles to improved energy efficiency. This is due to a lack of empirical evidence and because the barriers are so intermingled.

Analysis of U.S. energy demand was first undertaken seriously in the mid-1970s, with efforts to collect data and to construct models. Most of these efforts were discontinued in the early 1980s, as can be seen by examining the references in this report. Determining how we can obtain cost-effective energy efficiency requires, first, data on how energy is used, comparable in detail to the data collected on energy supply. Next, "energy conservation supply curves" must be carefully constructed to show which technologies are cost effective at various energy prices. A few examples of such data for the buildings and industrial sectors are given in Appendix C. For most technologies they are not available. Then information must be obtained to show how the market reacts to changing conditions (for example, demand elasticities with respect to prices and incomes). Finally, one must have information about responses to non-price policies and programs (for example, information programs, rebates, on-site energy audits, codes and standards). Experience with energy conservation programs shows that retrospective analysis of available data is often insufficient in determining consumer response. Thus, successful efforts have often been guided by an initial pilot program.

In the buildings sector the present study was limited by lack of available information in several areas. For example, efficiency improvements for residential and commercial lighting were omitted. Turnover of existing equipment was not accelerated in the cost-effective efficiency scenario. Retrofit of commercial buildings was not fully represented in the model although studies have indicated that the existing commercial building stock could be retrofitted to cut their energy consumption by 40 to 50 percent.[31]

Analysis of transportation technologies suffers from lack of consensus on what technologies are possible, how much they will cost, and consumer response. On the one hand, a 1989 four-passenger car is already available with an EPA rating of 65 mpg (the GEO Metro), and prototypes have been built with even better fuel economy.[32] In contrast, U.S. auto manufacturers maintain that only small increases can be realistically expected above present average performance levels of around 28 mpg. For other transportation modes there is a similar lack of systematic assessment of the performance of emerging technologies.

A major impediment to better understanding the industrial energy-efficiency potential is the long neglect of assessment. The use of a simple accounting model in this study illustrates the fact that no up-to-date industrial demand model with detail greater than the two-digit SIC level is available. The Industrial Sector Utilization Model is now available for personal computer application and could be quite useful. However, the model requires extensive data and these have not been updated since the late 1970s.

VI. EXTENDING THE LIMITS

In Chapters III and IV we examined energy-efficiency improvements that will be economically important before 2010. When we look further into the future, to the middle of the 21st century for example, the opportunities for additional efficiency are largely in the realm of research and development. Numerous promising technologies have been demonstrated to be scientifically feasible but are not yet developed. Some are developed but not yet used widely because of a need for reduced cost or merely the conservatism of consumers when confronted with new products. In general, these technologies will not make a big impact on energy use in the next 20 years, but will be increasingly important subsequently.

It generally takes much longer to develop and implement new technologies than initially estimated. Thus the research and development programs of the 1990s will have important economic consequences in the post-2010 period.

The continuing development of new technologies means that the limits to energy efficiency are a constantly moving target. Technical performance levels for equipment and buildings that seemed visionary a few years ago are now commonplace. In this chapter we review a few of the developments that are likely to improve energy utilization in the longer term.

BUILDINGS

For each application of energy-using equipment, maximum efficiency potential can be defined from theoretical (for example, thermodynamic) principles. For some end uses, such as furnaces, the current most efficient models are near the maximum First Law potential [for example, 97 percent annual fuel utilization efficiency (AFUE)]. But even here, new technologies, such as gas-fired heat pumps, provide potential for significant improvements, with the capability to achieve a coefficient of performance greater than 100 percent AFUE.

For other applications, current technology is far from the maximum achievable. For example, while there have been impressive efficiency improvements for refrigerators in the last 17 years, advanced insulations could still reduce energy consumption enormously. Several alternative designs of vacuum panel insulation are being researched, offering the potential for additional major energy savings while at the same time eliminating the chlorinated fluorocarbons (CFCs) used in polyurethane foam today, and the environmental threat they pose to the Earth's ozone layer. Additional research is now recognized as essential for developing alternative refrigerants to the CFCs for use in refrigeration and air conditioning units. The added challenge of ozone-safe refrigerants that are also more energy efficient than CFCs is important.

In many cases, it is not new inventions, but new ways of using existing devices that can have enormous payoffs. Control systems utilizing microchip devices could be substantially more sophisticated, without being expensive. Controls on heating and cooling systems, lighting, and other equipment, which are sensitive to the presence of occupants, or which can be adjusted from a distance (by phone, for instance) offer significant efficiencies. More intelligent control systems may be self-correcting, capable of remembering schedules or special circumstances, or of looking forward, based on measurements of outside temperature, for example, to anticipate changing conditions and adapt efficiently.

Variable-speed controls are technologies apparently on the verge of improving efficiencies for a wide range of applications, including fans, motors, and pumps.

Different applications could be linked; for instance, using waste heat from refrigerators or air conditioners to heat water, instead of a water heater. In the Philippines, a new appliance provides hot water, air conditioning, and cold water. In the United States, integrated space and water heaters exist, and research is ongoing on gas-fired units to provide space heating, water heating, and air conditioning. Individual cogeneration units may provide heat and electricity to an individual building.

Research in Sweden has advanced the understanding of buildings as integrated systems, and led to production of energy-efficient manufactured housing. Much could be learned from their experience that is applicable to buildings in the United States.

Thinking beyond the individual building, blocks of buildings could be treated as a system, as in district heating and cooling. The issue of urban heat islands appears to be an important one, offering opportunities for inexpensive reductions in energy consumption, with additional local and global environmental benefits.

New window designs, including super-insulating windows and low-emissivity films, could dramatically reduce the sensitivity of interior temperature to outside conditions.

In principle, buildings could be sufficiently well insulated that heating would be needed rarely, if ever. Passive solar designs, plus the heat contributions from occupants and equipment, could take care of heating requirements in many climates. On the other hand, much of air-conditioning energy might be displaced by passive dehumidification, for example, with desiccants.

In this report, we have not addressed peak power issues, but only energy savings. There are a number of strategies for demand-side management that will save resources at the power plant. More research is needed on energy demands as a function of time, such as load profiles for electric equipment. Smarter meters could be developed to facilitate more sophisticated pricing mechanisms, such as time-of-day pricing.

TRANSPORTATION

Beyond 2010, alternatives to petroleum are likely to dominate the search for fuel efficiency in the transportation sector. The continuing decline in U.S. crude oil production and concern over environmental issues will particularly affect transportation, with its heavy reliance on petroleum. Ethanol or methanol from biomass is one alternative. Another is the use of electric or hybrid vehicles, because electricity can be generated with a variety of fuel sources.

Improvements in battery technology are the key to significant use of electric vehicles. Early expansion of electric vehicles will likely be a result of the use of one of the three near-term battery technologies capable of 100- to 150-mile range. These are lead-acid, nickel-iron, and sodium-sulfur, each with its own technical hurdles. Later expansion might result from the replacement of these battery types with longer-term technologies including sodium-iron chloride, zinc-bromine, flow-through lead-acid, lithium-iron sulfide, iron-air, or sodium-nickel chloride. The Patterson study[1] does not project much penetration of electric vehicles, even at $3.00 per gallon gasoline. Hybrid vehicles are even more expensive than electric vehicles for the same level of performance because they carry two power systems. In the event of rapid depletion of oil reserves or extreme concern over global warming, however, these technologies might obtain a substantial share of the market after developing a foothold by 2010.

Scientists at the International Institute of Applied Systems Analysis (IIASA) have recently projected that natural gas will become the dominant world fuel in the 1990s and will capture over 60 percent of the world energy market by about 2030.[2] If the IIASA projections are correct, then natural gas may be expected to capture a large share of the transportation fuels market. There are several ways this can happen. Electricity can be generated from natural gas, methanol or synthetic gasoline can be made from natural gas, or vehicles can run on liquified or compressed natural gas (CNG). The leading candidates today are methanol and CNG. Methanol has a number of problems, but they do not seem insurmountable.[3,4] The first methanol vehicles are likely to use slightly modified engines capable of running either on gasoline or methanol, even though a more efficient engine can be designed if based on methanol only[5,6] and may be more than 20 percent more efficient than gasoline engines. Fuel cells operating with methanol are another possibility.

CNG and electric vehicles have limited range but are suitable for some urban driving applications. To provide range equivalent to current gasoline vehicles the costs and performance would have to be compromised seriously. Although gasoline can be made from natural gas, the cost and energy efficiency seem unattractive.

Use of methanol and CNG in trucks is also being explored. Current research suggests that methanol is less suited as a substitute for diesel fuel than for gasoline,[7] but it may ultimately be used as a replacement for diesel fuel in spark-assisted diesel engines.

In air transportation there are similar substitution possibilities. Liquified methane and hydrogen are listed as alternative fuels for aircraft by Swihart.[8] Methanol, which is very corrosive to aluminum and much more expensive than jet fuel, is probably not suitable. It thus seems likely that methanol will be used in cars to free up petroleum for use in aircraft. Liquid hydrogen is estimated to be necessary for use in aircraft flying above Mach 6. A hydrogen engine can be expected to be more efficient than a petroleum-fueled engine, but until Mach 6 to 12 speeds are reached, the cost penalties relative to petroleum will be prohibitive.

Scientists at the Argonne National Laboratory[9] have proposed the connection of major cities by magnetically levitated vehicles above elevated guideways and traveling at 200 to 300 miles per hour. Such a system would replace some highway traffic and commercial aircraft flying on short, less efficient routes. This would be an electrically driven transportation system. The system proposed by Johnson[9] was estimated to save 0.4 to 0.5 QBtu of petroleum fuel per year. The development of high-temperature superconducting materials may greatly increase the attractiveness and efficiency of both magnetically levitated vehicles and magnetically propelled ships.

Other advanced technologies that have been proposed to reduce energy consumption for transportation are fully automated highways and traffic control systems, "urban" cars for limited applications such as commuting, and substitution of advanced telecommunications for some transportation. Although there are many practical difficulties in the wide-scale implementation of such systems, it should be noted that traffic systems management through high-occupancy-vehicle lanes and computerized traffic control systems is being applied on an increasing scale.

INDUSTRIAL

Numerous opportunities exist for development of industrial processes with greater efficiency. Department of Energy research and development programs are investigating a number of specific processes, and industrial firms are doing research in others. Some idea of the potential can be obtained from estimated Second Law efficiencies as shown below.[10]

Industry	Existing efficiency (%)
Iron and steel	25
Aluminum	15
Petroleum refining	12
Pulp and paper	< 2
Chemicals	< 2

The pulp and paper industry uses three-fourths ton of oil per ton of paper produced. Ideally, the industry should be able to supply all its own energy from lignin wastes and not require any purchased fuel.

The advanced technologies discussed below promise significant reductions in energy use. Developments are discussed for both cross-cutting technologies and industrial groups.

Sensors and controls are of increasing importance in the industrial sector. They are used to measure many different parameters (temperatures, pressures, flow rates, etc.) in a variety of harsh environments (high temperature, high pressure, corrosive, etc.). Improved hardware technology is needed to provide sensors that can function accurately in these hostile environments and better software technology is needed to allow for more responsive control capability.

Variable speed controls for motors are currently available for application on existing and new equipment to adjust the speed control so that the motor and driven equipment can match the requirement of the process. Currently, variable speed controls are being installed but they are very expensive.

Motors account for about 64 percent of the electric energy consumed.[11] The potential for conserving energy by applying **high-temperature superconductors** in place of conventional conductors in industrial motors is very large. The advantages include reduced volume and mass, higher power density, enhanced performance, and improved operating efficiency.

Catalysts are used in many industries to produce chemical reactions at a lower pressure and temperature, thereby using less energy. Better understanding of the basic mechanisms of catalysts may lead to new classes of catalysts. These could be beneficial in the areas of one-step conversion of methane to methanol, photocatalytic reduction of water, combustion enhancement, and pollution control.[12]

Industrial **separation** processes (separation of the components in a mixture) are highly energy-intensive. Advancement of alternative processes that are less energy-intensive (membrane separation, freeze concentration, solvent extraction, critical fluid extraction, and advanced drying concepts) could be beneficial to many applications (black liquor concentration in the pulp and paper industry, hot food processing wastewater concentration, dilute soluble food process stream concentration, chemical/petrochemical stream separation, and drying of products such as textiles and paper).[13]

Cogeneration is the simultaneous production of process heat and electric power. Providing moderate- or low-temperature heat as a by-product of the work from a heat engine is much more efficient than providing heat directly by burning fuel. Most typical cogeneration in industry converts only 10 to 15 percent of the energy into electricity.[14] A new technology being developed is the intercooled steam-injected gas turbine (ISTIG) which incorporates a modern aircraft engine.[15] The ISTIG can accommodate variable amounts of steam returned to the turbine combustor and therefore has a flexible electricity-to-heat ratio. Steam not returned to the turbine is used for process heat. With a full steam injection, 40 percent of the energy can be converted into electricity.

Recovery and reuse of **waste heat** offers significant opportunities for energy conservation. The development of cost-effective heat exchangers and thermal storage units is needed for the recovery of high-temperature reject heat. These gas streams are very corrosive with temperatures in the 3,000°F range.[16] The development of high-lift heat pumps could greatly enhance the utility of low-grade waste heat. The pinch technology design method (based on the Second Law of Thermodynamics) could be beneficial in identifying waste heat recovery opportunities.

Advanced processes in the **steel** industry are mostly major process changes that could revolutionize the industry. The Plasmasmelt method involves smelting partially reduced iron powder with pulverized coal by using heat supplied by a plasma system. Ore-to-powder steelmaking could reduce the energy consumed by 40 percent. Direct steelmaking could double or triple production rates compared to the blast furnace and offer a 30 percent reduction in energy savings. The energy required to produce steel from scrap is less than one-half that required to produce steel from raw materials. However, scrap contains residual elements that have adverse effects on the properties of the steel. Developments such as the Nucor thin slab casting process could result in substantial energy savings. The electric arc furnace is a well-established technology and because of its rapidly increasing market share, improvements continue to be researched (such as dc arc furnace, induction melting, scrap preheating, heat and dust recovery, and ladle refining).

Major process changes in **aluminum** production eliminate either the Bayer process or the Hall-Heroult process or both. Carbothermic reduction of aluminum ore or alumina has the potential for substantial energy savings. Aluminum trichloride electrolysis allows for more production per unit cell volume. New anode and cathode designs for the Hall-Heroult process are being developed. The permanent anode design would decrease the frequency of anode replacements and the wetted cathode might enable a reduction in the distance between the electrodes associated with a high voltage loss without a loss in current efficiency.

Conventional chemical pulping in the **paper and pulp** industry is dominated by the very energy-intensive kraft process.[17] The energy required to recycle paper is about one-half that required by the kraft process. Desired improvements in the recycle process concentrate on improving the process to remove color and filler. Improvements in the papermaking process focus on improved process control (better automation), process physics (higher speeds), and improved materials (higher pressure rollers). These improvements would have a substantial effect on decreasing energy consumption. The three most promising advanced processes (biopulping, chemical pulping with fermentation, and ethanol organosol pulping) involve integration of at least one fermentation process with a conventional pulping process.

SUMMARY

As this chapter illustrates, there is ample evidence that we are not even close to fundamental limits in energy efficiency. Environmental problems, the needs of developing nations, and resource depletion make it increasingly imperative that we use energy as efficiently as possible.

The efficiency gains of the past were made possible by research and development. In their relatively short history, DOE conservation programs have produced technologies that are projected to reduce energy consumption in 2010 by more than 2 QBtu.[18] Fulkerson et al.[19] estimate current research and development expenditures on energy efficiency by the Department of Energy, Gas Research Institute, and Electric Power Research Institute at $250 million per year and recommend that the programs be augmented by an additional $300 million per year. For maximum effectiveness these efforts should be closely coordinated with industrial, utility, state, and local programs.

The research and development must be undertaken now in order to make a major contribution in the decades following the year 2010.

APPENDIX A

NOTES AND REFERENCES

CHAPTER II

1. Historical data on energy consumption and GNP are from *Monthly Energy Review May 1989*, DOE/EIA-0035(89/05), U.S. Energy Information Administration, August 1989.

2. Conceptually, energy efficiency represents the amount of useful energy service obtained per unit of primary energy input. Measurable indicators of energy efficiency include the following. Average passenger car efficiency increased from 13.3 mpg in 1973 to 19.2 mpg in 1988. Residential energy use declined from 215 million Btu per household in 1973, to 176 million Btu per household in 1987.

3. Some recent examinations of technical potential are given in J. Goldemberg, T. B. Johansson, A. K. N. Reddy, and R. H. Williams, *Energy for a Sustainable World*, Wiley Eastern Limited, New Delhi, India, 1988; T. B. Johansson, B. Bodlund, and R. H. Williams, eds., *Electricity—Efficient End-Use and New Generation Technologies, And Their Planning Implications*, Lund University Press, Lund, Sweden, 1989; and *Energy Conservation Multi-Year Plan 1990-1994*, U.S. Department of Energy, Office of Conservation, August 1988. A large number of assessments of energy efficiency took place in the 1970s. Some of the best known are: Solar Energy Research Institute, *A New Prosperity—Building a Sustainable Energy Future*, Brick House Publishing, Andover, Mass., 1981; *Alternative Energy Demand Futures to 2010*, The National Research Council, 1979; R. W. Sant, *The Least Cost Energy Strategy*, Carnegie-Mellon University Energy Productivity Center, Arlington, Va., 1979; and R. Stobaugh and D. Yergin, *Energy Futures*, Random House, New York, 1979.

4. Goldemberg et al., *Energy for a Sustainable World*.

5. Fuel price, demographic, and economic projections for 1990 to 2000 are from *Annual Energy Outlook 1989*, DOE/EIA-0383(89), U.S. Energy Information Administration, January 1989. Projections for 2000 to 2010 are a personal communication from Lynda T. Carlson, U.S. Energy Information Administration. These estimates show real prices of oil and gas rising about 4 to 5 percent per year, coal prices rising about 1 percent per year, and electricity prices nearly constant. Although EIA assumptions were changed later in 1989, we were not able to redo our analysis.

6. *The Most Energy-Efficient Appliances, 1988 Edition*, American Council for an Energy-Efficient Economy, Washington, D.C., 1988.

CHAPTER III

1. *Annual Energy Outlook 1989*, DOE/EIA-0383(89), U.S. Energy Information Administration, January 1989; and personal communication from Lynda T. Carlson, U.S. Energy Information Administration.

2. *Monthly Energy Review May 1989*, DOE/EIA-0035(89/05), U.S. Energy Information Administration, August 1989.

3. Brookhaven National Laboratory, *Analysis and Technology Transfer Annual Report—1987*, DOE/CH-00016-H1, U.S. Department of Energy, Office of Buildings and Community Systems, July 1988.

4. LBL-REM utilizes a large data base comprised of demographic and macroeconomic projections; detailed engineering information about many alternative designs of equipment and buildings; and economic parameters characterizing market decision-making regarding fuel, technology, and efficiency choice, and subsequent usage behavior. The projected number of households by house

type (single family, multifamily, mobile home) is estimated for ten Federal regions based on population growth and age composition. Current appliance holdings and main heating fuel are determined from surveys by the Bureau of the Census, the Department of Energy, and manufacturers. Turnover of existing appliances is projected based on empirical probabilistic aging functions. Future appliance purchases are a function both of turnover of existing appliance and building stocks, and of the number of new houses built each year.

New building characteristics are projected, based on projected energy prices. Retrofit expenditures for conservation measures applied to existing houses are projected based on household energy expenditures and income. Efficiencies of new appliances are projected based on the menu of designs possible, their costs, and energy prices, using decision-making typical of recent purchaser behavior, with specific account taken of Federal appliance standards. Changes in usage behavior are projected based on projected energy expenditures and income.

For more information, see *Technical Support Document: Energy Conservation Standards for Consumer Products: Dishwashers, Clotheswashers, and Clothesdryers*, DOE/CE-0267, Department of Energy, Office of Conservation and Renewable Energy, July 1989; and J. E. McMahon, "LBL Residential Energy Model: An Improved Policy Analysis Tool," *Energy Systems and Policy* 10(1), pp. 41–71, 1987.

5. The general economic and engineering structure of the National Commercial Energy Model was originally developed by Oak Ridge National Laboratory in the late 1970s. The present model is disaggregated to 12 building types, 8 end uses, and 3 fuel types. The floor space estimates and projections by building type have been calibrated to the 1986 Commercial Building Energy Consumption Survey published by the U.S. Energy Information Administration.

   The basic engineering estimates of the potential of energy-saving technologies were taken from a study of commercial buildings in New York State performed by Lawrence Berkeley Laboratory (LBL). Starting with seven prototypical buildings assumed to incorporate 1986 average efficiency levels, LBL performed engineering simulations of various conservation technologies. For each conservation measure, a "cost of saved energy" was estimated, based on the first cost of the measure, incremental maintenance costs, and the life of the measure.

   The engineering and cost analysis yields two estimates of the percentage reduction in electricity consumption—the first corresponding to private market perspective and the second corresponding to a societal perspective. For example, the simulation analysis of the education building resulted in a 12 percent saving in the business as usual (35 percent discount rate) case and an additional 22 percent saving in the societal perspective, or conservation, case (7 percent discount rate). The second percentage represents untapped potential that may require some type of governmental action.

6. D. J. Santini and A. D. Vyas, *Theoretical Basis and Parameter Estimates for the Minority Transportation Expenditure Allocation Model (MITRAM)*, ANL/ES-159, Argonne National Laboratory, Argonne, Ill., December 1988. The values presented were constructed by members of Argonne National Laboratory's Center for Transportation Research using the TEEMS modeling system, professional judgment, and some modeling work done for this project and for related studies being conducted by the Office of Environment and Office of Transportation Systems, U.S. Department of Energy. We used detailed indexes of sectoral output created by running the DRI macromodel for a similar projection of economic activity. These indexes (not presented) provided the basis for our estimates of the degree of expansion of freight ton-miles.

   Several modifications to the TEEMS model outputs were made during this study. These modifications included adding an estimate of the use of fuel by general aviation and by the military. We have no information of the trends in fuel efficiency in the military and assume no change in efficiency of military aircraft in either projection during the study period. We assumed in both projections a 0.2 percent per year efficiency gain for general aviation, a very small fuel consumer. TEEMS contains no equations projecting fuel oil use from vessel bunkering. Statistics from *Basic Petroleum Data Book* IX(2), American Petroleum Institute, Washington, D.C., May 1989, were used to compile a bunkering residual oil sales estimate and, in that case, we projected residual fuel use in transportation using growth rates obtained from U.S. Energy Information Administration data. We added electric rail transit, using a 1985 value from the *National Transportation Statistics Annual Report 1988*, DOE-TSC-RSPA-88-2, U.S. Department of Transportation, August 1987. We assumed an annual growth rate of electric rail transit use of 0.5 percent per year in both projections.

7. F. Westbrook and P. Patterson, "Changing Driving Patterns and Their Effect on Fuel Economy," presented at the 1989 SAE Government/Industry Meeting, May 2, 1989, Washington, D.C.

8. *Basic Petroleum Data Book* IX(2), American Petroleum Institute, Washington, D.C., May 1989.

9. L. S. Williams and P. S. Hu, *Light Duty Vehicle Summary: Model Year 1976 to the First Half of Model Year 1989*, Oak Ridge National Laboratory, Oak Ridge, Tenn., August 1989.

10. Williams and Hu, 1989.

11. W. U. Chandler, H. S. Geller, and M. R. Ledbetter, *Energy Efficiency: A New Agenda*, American Council for an Energy-Efficient Economy, Washington, D.C., July 1988.

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13. This total includes agriculture, mining, and construction (that is, non-manufacturing industry), and also includes electric generation losses to provide power to industry. Excluding non-manufacturing industry, the sector total for 1988 was 21 to 22 QBtu. The reader should note, however, that various U.S. Department of Energy, Energy Information Administration sources give inconsistent totals for industry. See *Monthly Energy Review*, U.S. Energy Information Administration; *Manufacturing Energy Consumption Survey: Consumption of Energy, 1985*, DOE/EIA-0512(85), U.S. Energy Information Administration, November 1988; "FY 1991 Energy Conservation Multi-Year Plan," U.S. Department of Energy, Office of Conservation, draft, 1989. This modeling exercise, and the totals reported in the text, are based on *Monthly Energy Review February 1989*, DOE/EIA-0035(89/02), U.S. Energy Information Administration, May 1989.

    Petrochemical feedstocks and energy consumed for asphalt, lubricants, and similar products are included in manufacturing energy consumption in this report.

14. J. M. Roop and D. B. Belzer, *Changes in the Structure of the U.S. Economy: An Input-Output Analysis*, PNL-SA-35961, Pacific Northwest Laboratories, Richland, Wash., 1987.

15. This statement is based on a Pacific Northwest Laboratories informal survey of trade association publications and representatives, including *The Aluminum Statistical Review*, The Aluminum Association, Washington, D.C., 1987; *1988 Annual Statistical Report*, American Iron and Steel Institute, New York; and *Annual Energy Report*, American Iron and Steel Institute, New York, June 2, 1989. A precise evaluation of recent trends, however, has been made virtually impossible by diminishing attention to this issue during the 1980s, particularly the expiration of the Industrial Energy Conservation Reporting Program.

16. *Annual Report to the Congress and the President on Industrial Energy Efficiency Improvement*, U.S. Department of Energy, Office of Industrial Programs, 1985; Solar Energy Research Institute, *A New Prosperity*; National Research Council, National Academy of Sciences, Committee on Nuclear and Alternative Energy Systems, *Energy in Transition 1985-2010*, W. H. Freeman, San Francisco, 1979; "Energy Conservation Multi-Year Plan 1991-1995," U.S. Department of Energy, Office of Conservation, draft, July 1989.

    It should be noted, however, that most such studies are five to ten years old, due to the virtual absence of U.S. government support for energy efficiency research during the 1980s.

17. This model is the "EPA Energy End-Use Model," developed by Irving Mintzer of the World Resources Institute, and modified by William U. Chandler and Stanislav Kolar of Battelle Pacific Northwest Laboratories. For a description of the original model structure, see Irving Mintzer, "Projecting Future Energy Demand in Industrialized Countries: An End-Use Oriented Approach," World Resources Institute, Washington, D.C., draft, October 1988. A copy of the model can be obtained from Pacific Northwest Laboratories.

    The user specifies initial demand for oil, gas, coal, and electricity for six major industry categories by two-digit standard industrial classification (SIC). These categories, or subsectors, are identified in Appendix C, Table C-7. The user also provides initial activity levels for each sector. Using these data, the model calculates initial sectoral energy intensity coefficients. We concentrate on basic industries such as steel, chemicals, aluminum, and cement because they (with petroleum refining) consume over three-quarters of the energy consumed in manufacturing. Structural change is characterized as the ratio of the growth of each of the subsectors listed in Table C-7 (Appendix C) to growth in GNP.

    Structural change assumptions affect the energy intensity of the overall economy because shifting levels of energy-intensive activities (for example, steel output as a share of GNP) change the energy required per unit of economic output. (This rate should not be confused with energy efficiency changes.) Both GNP growth and sectoral growth rate ratios are exogenous assumptions provided by the user.

    The model projects future energy demand on the basis of three other important factors. First, it incorporates energy price response, which the user exogenously specifies by selecting rates of change for oil, gas, coal, and electricity prices in the industrial sector, and price elasticities of demand for each industrial sub-sector. Second, the model modifies future energy demand estimates with a so-called technical factor, which is essentially a rate of change in energy intensity per unit of industrial activity—over and above the price response. This factor is justified empirically, and is exogenous (see James A. Edmonds and John M. Reilly, *Global Energy: Assessing the Future*, Oxford University Press, New York, 1985). Third, the model permits the user to specify a price cross-elasticity of demand for electricity which determines the rate of change in electricity demand as a function of the difference between fuel price and electric price changes.

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21. Edmonds and Reilly, *Global Energy*; Douglas R. Bohi, *Analyzing Demand Behavior: A Study of Energy Elasticities*, Johns Hopkins University Press, Baltimore, 1981.

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23. "Frozen efficiency" energy consumption was calculated as follows for each subsector. Present energy intensity was multiplied by the activity level projected in the "Where We Are Headed" scenario for the target year. For example, in the freight transportation sector, the 1985 energy intensity was 1,477 Btu per ton-mile, and the projected activity level in 2010 was $6{,}932 \times 10^9$ ton-miles. The 2010 frozen efficiency energy consumption is therefore 10.2 QBtu.

24. The column "DOE/PE reference case" is from *Long-Range Energy Projections to 2010*, DOE/PE-0082, U.S. Department of Energy, Office of Policy, Planning and Analysis, July 1988. The column "GRI baseline" is from P. D. Holtberg et al., *1989 GRI Baseline Projection of U.S. Energy Supply and Demand to 2010*, Gas Research Institute, Strategic Planning and Analysis Division, Washington, D.C., December 1989. The column "DRI forecast" is from *Energy Review* 13(2), Data Resources, Inc., Lexington, Mass., Summer 1989. The column "DOE/EIA base case" is from *Annual Energy Outlook 1989*, DOE/EIA-0383(89), U.S. Energy Information Administration, 1989; and personal communication from Lynda T. Carlson, U.S. Energy Information Administration, July 18, 1989.

CHAPTER IV

1. Cost of conserved energy (CCE) is defined as the ratio of increased cost (for more efficient equipment or buildings) to the product of energy saved annually times present worth factor (PWF). The PWF includes a discount rate and the lifetime of the efficiency measure.

$$CCE = \frac{\text{cost of conservation measure}}{\text{energy saved per year} \times \text{PWF}} \text{ , and}$$

$$PWF = (1/r)[1 - (1 + r)^{-t}] \text{ ,}$$

where r = discount rate and t = lifetime (years) of the conservation measure.

2. Variable air volume (VAV) systems are air transport systems that respond to changes in heating or cooling load by reducing the amount of conditioned air to the space. VAV systems can be put into most types of new commercial buildings as well as into many existing buildings. VAV systems have the potential of saving 5 to 15 percent of total electricity usage as compared to conventional systems.

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APPENDIX B

POPULATION, GNP, AND PRICE OF ENERGY BY SOURCE AND END-USE SECTOR

Table B-1. Population, GNP, and price of energy by source and end-use sector
1988 dollars per million Btu, except where noted

Sector and fuel	1988	1990	1995	2000	2005	2010
Residential	**10.83**	**11.08**	**12.12**	**13.60**	**14.96**	**16.45**
Primary energy	5.47	5.62	6.67	7.95	9.33	10.95
Petroleum products	5.96	6.24	7.85	9.68	11.88	14.59
Distillate fuel	5.80	5.99	7.29	8.87	10.62	12.71
Liquified petroleum gas	6.38	6.90	9.12	11.34	14.49	18.51
Natural gas	5.34	5.45	6.35	7.48	8.60	9.90
Steam coal	2.73	2.77	2.90	3.06	3.22	3.38
Electricity	22.21	22.39	21.84	22.43	22.54	22.66
Commercial	**11.28**	**11.54**	**12.39**	**13.76**	**14.98**	**16.31**
Primary energy	4.53	4.53	5.54	6.79	8.05	9.54
Petroleum products	4.61	4.38	5.82	7.54	9.30	11.48
Distillate fuel	4.72	4.32	5.60	7.15	8.52	10.15
Residual fuel	2.44	2.62	3.62	4.67	6.18	8.18
Other petroleum	6.65	6.65	8.62	10.56	12.83	15.60
Natural gas	4.61	4.70	5.56	6.67	7.79	9.09
Steam coal	1.56	1.58	1.66	1.75	1.84	1.93
Electricity	20.98	21.18	20.65	21.24	21.35	21.45
Industrial	**4.55**	**4.63**	**5.61**	**6.82**	**8.08**	**9.58**
Primary energy	3.01	2.99	4.01	5.12	6.41	8.03
Petroleum products	3.62	3.46	4.91	6.34	8.06	10.25
Distillate fuel	3.91	4.42	5.71	7.28	9.49	12.37
Liquified petroleum gas	4.35	4.30	6.48	8.64	11.60	15.59
Motor gasoline	6.98	6.65	8.48	10.30	12.15	14.33
Residual fuel	2.24	2.11	3.13	4.16	5.42	7.07
Other petroleum	3.34	2.93	4.07	5.04	6.00	7.15
Natural gas	2.79	2.91	3.76	4.85	6.13	7.76
Metallurgical coal	1.76	1.78	1.85	1.94	2.02	2.10
Steam coal	1.54	1.56	1.62	1.69	1.76	1.83
Hydroelectric power	12.31	12.31	12.31	12.31	12.31	12.31
Electricity	14.11	14.33	13.79	14.35	14.42	14.49
Transportation	**6.42**	**6.40**	**7.98**	**9.61**	**11.39**	**13.50**
Primary energy	6.41	6.39	7.97	9.60	11.38	13.49
Petroleum products	6.41	6.39	7.97	9.60	11.38	13.49
Distillate fuel	6.13	6.47	7.76	9.31	11.09	13.21
Jet fuel	3.81	3.76	5.12	6.56	8.26	10.39
Motor gasoline	6.98	6.91	8.74	10.55	12.57	14.97
Residual fuel	2.26	2.00	3.01	4.04	5.19	6.66
Other petroleum	19.70	19.42	20.57	21.53	22.30	23.09
Electricity	19.86	20.13	19.62	20.26	20.46	20.67
Economic variables						
Real GNP (billion 1982 $)	4001	4217	4757	5368	6073	6871
Population (million persons)	245.6	250.0	259.9	268.4	277.9	287.8

Adapted from U.S. Energy Information Administration, *Annual Energy Outlook 1989*, Tables A3 and A11, and personal communication with Lynda T. Carlson, U.S. Energy Information Administration. Electricity is converted at 3412 Btu/kWh.

APPENDIX C

ENERGY CONSUMPTION AND ENERGY INTENSITY

Table C-1. Where we are headed—buildings sector

	1985	1988	1990	1995	2000	2005	2010
Primary energy by subsector, QBtu							
Residential							
Space heat	6.5		7.0	7.1	7.3	7.5	7.7
Water heat	2.8		2.9	3.1	3.2	3.4	3.7
Refrigerator	1.9		2.0	1.8	1.7	1.7	1.8
Air conditioning	1.1		1.2	1.2	1.4	1.5	1.6
Other	3.7		4.1	4.5	4.8	5.2	5.6
Total	16.0		17.2	17.7	18.4	19.3	20.4
Commercial							
Space heat			4.1		4.5		5.1
Air conditioning			1.3		1.6		1.9
Ventilation			1.6		1.9		2.3
Lighting			3.3		4.2		4.9
Other			2.8		3.8		4.6
Total	10.8		13.1		16.0		18.8
Total-buildings	26.8		30.3		34.4		39.2
Primary energy by fuel type, QBtu							
Electricity	16.9	18.7	19.3		23.8		28.4
Oil	2.6	2.7	2.1		2.0		4.0
Natural gas	7.1	7.5	8.4		8.1		6.3
Coal/other	0.2	0.2	0.5		0.5		0.5
Total-buildings	26.8	29.1	30.3		34.4		39.2
Energy intensity							
Residential (MBtu/household)			180		166		162
Commercial (kBtu/square foot)			206		204		201

Note: Attribution of residential energy consumption to end uses has not been calibrated with recent RECS results, which indicate that the share of electricity used for space heat is lower. The increasing share for electric space heat is a result of the energy price projection (Appendix B), in which electricity prices do not rise appreciably, while fossil prices do increase.

Table C-2. Where we are headed—transportation sector

	1985	1988	1990	1995	2000	2005	2010
Primary energy by subsector, QBtu							
Personal vehicles							
Autos	7.4		7.8	7.7	7.8	7.5	7.3
Trucks	1.8		2.1	2.4	2.3	2.2	2.0
Total-personal	9.2		9.9	10.1	10.1	9.7	9.3
Air travel	1.7		1.9	2.0	2.2	2.4	2.7
Freight							
Trucks	4.7		5.3	5.5	5.9	6.5	7.1
Rail	0.4		0.5	0.6	0.7	0.8	0.9
Marine	0.3		0.3	0.3	0.4	0.4	0.4
Air	0.1		0.1	0.1	0.1	0.1	0.1
Pipeline	0.7		0.7	0.7	0.7	0.7	0.7
Total-freight	6.2		6.9	7.2	7.8	8.5	9.2
Other subsectors[a]	3.0		3.0	3.1	3.1	3.1	3.1
Total-transportation	20.1	21.9	21.7	22.4	23.2	23.7	24.3
Primary energy by fuel type, QBtu							
Gasoline	12.6		13.3	13.4	13.3	12.8	12.4
Diesel	3.4		4.2	4.6	5.1	5.8	6.5
Jet fuel	2.5		2.8	2.9	3.1	3.4	3.6
Natural gas	0.5		0.5	0.6	0.6	0.6	0.6
Other	1.1		0.9	0.9	1.1	1.1	1.2
Total-transportation	20.1	21.9	21.7	22.4	23.2	23.7	24.3
Energy efficiency							
Personal vehicles (mpg)							
Autos	17.9		19.1	20.3	21.5	23.7	26.2
Trucks	14.5		15.5	16.5	17.5	19.3	21.3
Total-personal	17.2		18.3	19.5	20.6	22.8	25.2
Air travel (passenger-miles/kBtu)	0.16	0.18	0.20	0.21	0.23	0.25	
Freight (ton-miles/kBtu)							
Trucks	0.35		0.37	0.40	0.42	0.43	0.45
Rail	2.01		2.03	2.07	2.12	2.15	2.17
Marine	2.72		2.70	2.70	2.68	2.67	2.65
Air	0.05		0.05	0.06	0.07	0.08	0.09
Pipeline	1.16		1.13	1.04	1.00	0.98	0.97
Total-freight	0.68		0.68	0.70	0.72	0.74	0.75

[a]Fleet vehicles, buses, general aviation, military aviation, foreign vessel bunkering, and electric rail transportation.

Table C-3. Where we are headed—industrial sector

	1985	1988	1990	1995	2000	2005	2010
Primary energy by fuel type, QBtu							
Electricity	9.5	9.9	10.8	12.4	14.1	17.0	18.3
Oil	7.7	8.7	7.9	8.0	8.0	8.4	8.1
Natural gas	7.1	7.7	7.4	7.5	7.7	8.2	8.0
Coal	2.8	2.8	3.0	3.2	3.4	3.6	3.8
Total-industrial	27.1	29.1	29.1	31.1	33.2	37.2	38.2
Energy intensity							
Energy intensity per dollar of industrial output (1985 = 100)	100		96		90		85

Table C-4. Cost-effective efficiency—buildings sector

	1985	1988	1990	1995	2000	2005	2010
Primary energy by subsector, QBtu							
Residential							
Space heat	6.5		6.9	6.5	6.5	6.6	6.8
Water heat	2.8		2.9	2.8	2.7	2.8	3.0
Refrigerator	1.9		1.9	1.7	1.4	1.2	1.2
Air conditioning	1.1		1.2	1.2	1.2	1.3	1.5
Other	3.7		4.2	4.3	4.6	5.0	5.2
Total	16.0		17.1	16.5	16.4	16.9	17.7
Commercial							
Space heat			4.1		4.1		4.4
Air conditioning			1.3		1.5		1.6
Ventilation			1.6		1.8		1.9
Lighting			3.3		3.9		4.2
Other			2.8		3.5		4.0
Total	10.8		13.1		14.8		16.1
Total-buildings	26.8		30.2		31.2		33.8
Primary energy by fuel type, QBtu							
Electricity	16.9	18.7	19.3		21.7		24.5
Oil	2.6	2.7	2.1		1.8		1.8
Natural gas	7.1	7.5	8.3		7.3		7.1
Coal/other	0.2	0.2	0.5		0.4		0.4
Total-buildings	26.8	29.1	30.2		31.2		33.8
Energy intensity							
Residential (MBtu/household)			180		148		140
Commercial (kBtu/square foot)			206		190		172

Note: Attribution of residential energy consumption to end uses has not been calibrated with recent RECS results, which indicate that the share of electricity used for space heat is lower. The increasing share for electric space heat is a result of the energy price projection (Appendix B), in which electricity prices do not rise appreciably, while fossil prices do increase.

Table C-5. Cost-effective efficiency—transportation sector

	1985	1988	1990	1995	2000	2005	2010
Primary energy by subsector, QBtu							
Personal vehicles							
Autos	7.4		7.8	6.4	5.8	5.4	5.0
Trucks	1.8		2.1	2.2	2.1	1.9	1.8
Total-personal	9.2		9.9	8.6	7.9	7.3	6.8
Air travel	1.7		1.9	2.0	2.0	2.1	2.1
Freight							
Trucks	4.7		5.3	5.4	5.6	6.0	6.5
Rail	0.4		0.5	0.6	0.7	0.8	0.9
Marine	0.3		0.3	0.3	0.3	0.3	0.4
Air	0.1		0.1	0.1	0.1	0.1	0.1
Pipeline	0.7		0.7	0.7	0.7	0.7	0.7
Subtotal-freight	6.2		6.9	7.1	7.4	7.9	8.6
Other subsectors[a]	3.0		3.0	2.8	2.7	2.7	2.7
Total-transportation	20.1	21.9	21.7	20.5	20.0	20.0	20.2
Primary energy by fuel type, QBtu							
Gasoline	12.6		13.3	11.6	10.5	9.9	9.4
Diesel	3.4		4.2	4.5	4.9	5.4	6.0
Jet fuel	2.5		2.8	2.9	2.9	3.0	3.1
Natural gas	0.5		0.5	0.6	0.6	0.6	0.6
Other	1.1		0.9	0.9	1.1	1.1	1.1
Total	20.1	21.9	21.7	20.5	20.0	20.0	20.2
Energy efficiency							
Personal vehicles (mpg)							
Autos	17.9		20.2	23.9	28.1	32.2	36.9
Trucks	14.5		15.5	17.8	20.8	23.3	26.2
Total	17.2		18.3	22.4	26.2	29.9	34.0
Air travel (passenger-miles/kBtu)	0.16		0.18	0.20	0.24	0.27	0.31
Freight (ton-miles/Btu)							
Trucks	0.35		0.37	0.41	0.45	0.47	0.49
Rail	2.01		2.04	2.08	2.14	2.17	2.20
Marine	2.72		2.70	2.70	2.68	2.67	2.65
Air	0.05		0.05	0.06	0.07	0.08	0.09
Pipeline	1.16		1.13	1.04	1.00	0.98	0.97
Total	0.68		0.68	0.72	0.76	0.79	0.81

[a]Fleet vehicles, buses, general aviation, military aviation, foreign vessel bunkering, and electric rail transportation.

Table C-6. Cost-effective efficiency—industrial sector

	1985	1988	1990	1995	2000	2005	2010
			Primary energy by fuel type, QBtu				
Electricity	9.5	9.9	10.8	12.4	14.1	17.0	18.3
Oil	7.7	8.7	7.6	7.3	7.0	7.0	6.5
Natural gas	7.1	7.7	7.0	6.8	6.6	6.8	6.3
Coal	2.8	2.8	2.9	2.8	2.8	2.9	2.8
Total-industrial	27.1	29.1	28.3	29.3	30.5	33.7	33.9
			Energy intensity				
Energy intensity per dollar of industrial output (1985 = 100)	100		93		83		76

Table C-7. Subsectors used in industrial model and their 1987 energy consumption

Two-digit SIC	Subsector	Total primary energy[a] QBtu	Percent share
29	Petroleum	5.7	21
28	Chemicals	5.2	19
33	Primary metals	3.8	14
26	Paper	3.1	11
32	Stone, clay, glass	1.3	31
	Subtotal	19.1	69
	Rest of industrial sector	8.6	31
	Total	27.7	100

[a]*Source*: for first five subsectors, *Manufacturing Energy Consumption Survey: Consumption of Energy, 1985*, DOE/EIA-0512(85), U.S. Energy Information Administration, 1985; total for industrial sector from *Monthly Energy Review February 1989*, DOE/EIA-0035(89/2), U.S. Energy Information Administration, May 1989.

Table C-8. The changing composition of U.S. industry

	Average annual growth rates,[a] 1976–1987		Annual growth rates (percent per year), 1988–2000	
	Percent per year	Relative to GNP	*Annual Energy Outlook*[a]	This study
GNP	2.84	1.00	2.5	2.5
Petroleum				1.25
Chemicals	2.55	0.90	4.0	2.50
Primary metals	-2.25	-0.79	1.9	0.63
Paper	2.47	0.87	2.8	2.00
Stone, clay, glass	0.17	0.06	1.8	1.25
Balance of industrial sector				2.00

[a]*Source*: *Assumptions for the Annual Energy Outlook 1989*, DOE/EIA-0527(89), U.S. Energy Information Administration, June 1989.

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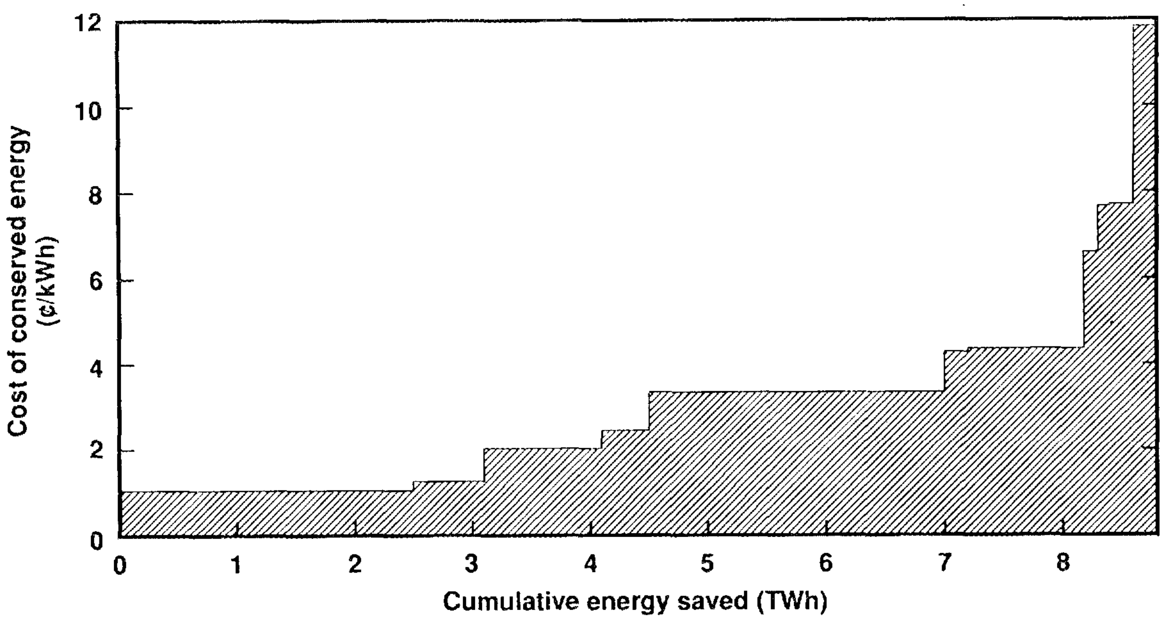

Fig. C-1. Conservation supply curve for residential electricity. The energy savings displayed are from measures implemented in the year 2000, not the cumulative savings accruing in that year due to measures implemented up until that time. The cumulative savings are captured in Table C-4.

Table C-9. Conservation supply curve for residential electricity in the year 2000

	Energy savings (TBtu)	Energy savings (GWh)	Cumulative energy savings (GWh)	Cost of conserved energy (cents per kWh)
Dishwasher	9.156	796.17	796.17	1.04
Washer	19.229	1672.09	2468.26	1.23
Dryer	7.237	629.30	3097.57	2.02
Building thermal integrity	11.208	974.61	4072.17	2.44
Freezer	5.522	480.17	4552.35	3.31
Refrigerator	27.742	2412.35	6964.70	4.24
Room air conditioner	2.322	201.91	7166.61	4.33
Cooking	4.633	402.87	7569.48	4.33
Central air conditioner	6.984	607.30	8176.78	6.58
Retrofit	0.967	84.09	8260.87	7.66
Miscellaneous	2.01	174.78	8435.65	7.7
Heat pump	1.794	156.00	8591.65	11.82

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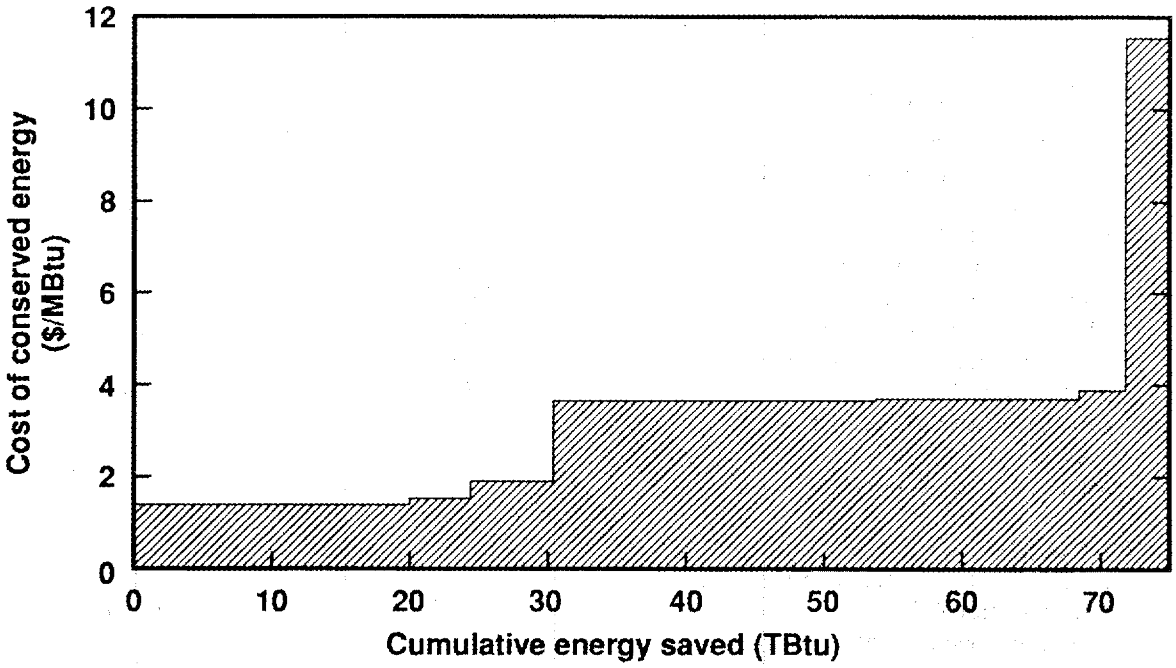

Fig. C-2. Conservation supply curve for residential gas. The energy savings displayed are from measures implemented in the year 2000, not the cumulative savings accruing in that year due to measures implemented up until that time. The cumulative savings are captured in Table C-4.

Table C-10. Conservation supply curve for residential gas in the year 2000

	Energy savings (TBtu)	Cumulative energy savings (TBtu)	Cost of conserved energy ($/MBtu)
Dishwasher	5.987	5.99	1.39
Washer	13.697	19.68	1.51
Building thermal integrity	4.74	24.42	1.87
Miscellaneous	5.986	30.41	3.63
Heating	23.344	53.75	3.67
Water heating	14.696	68.45	3.9
Retrofit	3.372	71.82	11.52

Table C-11. Projections of efficiencies of new residential equipment purchased in 2000

	Where we are headed	Cost effective at 7 percent real discount rate
Electric		
Heat pump (HSPF)[a]	7.32	7.73
Heat pump (SEER)[b]	10.08	11.27
Central air conditioner (SEER)	10.06	10.86
Room air conditioner (EER)[c]	8.92	9.32
Water heater (%)	89.85	97.00
Refrigerator (kWh/year)	914.9	588.8
Freezer (kWh/year)	587.0	351.6
Electric range/oven (relative value)	1.02	1.11
Electric clothes dryer (lb/kWh)	2.84	3.29
Dishwasher (loads/kWh)	0.37	0.44
Clothes washer (ft^3/kWh)	1.11	1.29
Lighting	*d*	*d*
Miscellaneous (relative value)	1.00	1.02
Natural gas		
Furnace, large central (AFUE, %)	81.50	93.45
Water heater (%)	58.54	76.36
Gas range/oven (relative value)	1.13	1.13
Gas clothes dryer (lb/kWh)	2.82	2.82
Miscellaneous (relative value)	1.07	1.14

[a]HSPF = heating seasonal performance factor.
[b]SEER = seasonal energy efficiency ratio.
[c]EER = energy efficiency ratio.
[d]Not analyzed.
Source: LBL Residential Energy Model.

Table C-12. Rates of industrial energy-efficiency improvement, 1972 to 2010

	Actual 1972-1985[b]	AEO[c]	Economically justifiable[a] SERI[d]	CONAES[e]	Ross[f]	DOE[g]	OTA[h]
Petroleum and coal	2.5	0.8	N/A	N/A	0.5	0.9	0.6
Chemicals	3.4	0.8	2.0	1.7	1.4	0.7	0.6
Iron and steel	2.1	0.8	1.8	0.9	1.0	2.4[i]	2.3
Paper	4.7	0.8	2.0	1.3	1.3	2.1[j]	1.3
Stone, clay, glass	2.6	0.8	1.9[k]	1.3[l]	N/A	N/A	N/A
Other	2.8	0.8	N/A	1.6	N/A	1.3[m]	N/A

[a]Benefit/cost ratio exceeds unity under conditions assumed for each study.

[b]*Source*: *Annual Report to the Congress and the President on Industrial Energy Efficiency Improvement*, U.S. Department of Energy, Office of Industrial Programs, 1985.

[c]*Source*: *Assumptions for the Annual Energy Outlook*, DOE/EIA-0527(89), U.S. Energy Information Administration, June 1989.

[d]*Source*: Solar Energy Research Institute, *A New Prosperity—Building a Sustainable Energy Future*, Brick House Publishing, Andover, Mass., 1981. Scrap and build scenario.

[e]*Source*: National Research Council, National Academy of Sciences, Committee on Nuclear and Alternative Energy Systems, *Energy in Transition 1985-2010*, W. H. Freeman, San Francisco, 1979. Scenario A, maximum efficiency.

[f]*Source*: M. Ross and G. Boyd, "Industrial Production and Energy Use: Recommendations for Long-Term Projections," draft discussion paper no. 6.1, Argonne National Laboratory, Argonne, Ill., 1984.

[g]*Source*: "FY 1991 Energy Conservation Multi-Year Plan," U.S. Department of Energy, Office of Conservation, draft, May 1989.

[h]*Source*: *Industrial Energy Use*, OTA-E-198, U.S. Congress, Office of Technology Assessment, 1983.

[i]Primary metals average.

[j]Commercial energy.

[k]Cement.

[l]Average of cement and glass subsectors.

[m]Unweighted average of machinery, transportation equipment, and other.

Table C-13. Energy-efficiency potential in the U.S. steel industry

Process stage	Savings potential[a] (MMBtu/ton)
Blast furnace	3.7
Cokemaking	3.0
Billet reduction mill	2.5
Ingot casting	1.9
Electric arc furnace	1.4
Cold rolling mill	1.3
Reheat furnace	1.2
Hot strip mill	1.0
Others	3.4
Total[b]	6–10
Current requirement per ton	25 MMBtu/ton
Year 2010 requirement	15–19 MMBtu/ton
Average annual reduction	-1.2 to -2.3 %/year[c]

[a] All listed savings have an estimated payback period between two and seven years.

[b] Savings potentials are not additive.

[c] The Office of Technology Assessment (*Industrial Energy Use*, OTA-E-198, 1983) also estimates an annual average reduction in energy intensity of U.S. steelmaking of -2.3 percent per year between 1980 and 2000.

Source: Sayed A. Azimi and Howard E. Lowitt, *The U.S. Steel Industry: An Energy Perspective*, DOE/RL-01383-T55, U.S. Department of Energy, January 1988.

Table C-14. Energy-efficiency potential in the U.S. aluminum industry

Measure	Savings potential[a] (MMBtu/ton)
Improved cells	26
Inert cathodes	26
Recycle 75% cans	3
Direct casting	2
Redesign remelt furnace	1
Total	58
Current requirement	160 MMBtu/ton
Year 2010 requirement	102 MMBtu/ton
Average annual reduction	-2.0 %/year

[a]All listed measures cost less than 3 cents/kWhe.

Source: J. V. Andersen, Idaho National Engineering Laboratory, unpublished memorandum, August 1989.

Table C-15. Energy-efficiency investment opportunities in the U.S. chemicals industry

Measure[a]	Levelized cost[b] ($/MMBtu saved)
High-efficiency electric motors	1.50
Cogeneration, ammonium nitrate plant	2.88
Computerized process controls	3.00
Regenerative heat exchangers	3.40
Waste-heat boiler, ammonia plant	3.66
Cogeneration, ammonia plant	3.81

[a]These measures represent selected opportunities from various processes within the chemical industry, as identified by the Office of Technology Assessment.

[b]Based on 10-year lifetime (except 7 years for computer controls), 7 percent discount rate, and (where applicable) installation at normal retirement of older equipment.

Source: Adapted from *Industrial Energy Use*, OTA-E-198, U.S. Congress, Office of Technology Assessment, 1983.

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