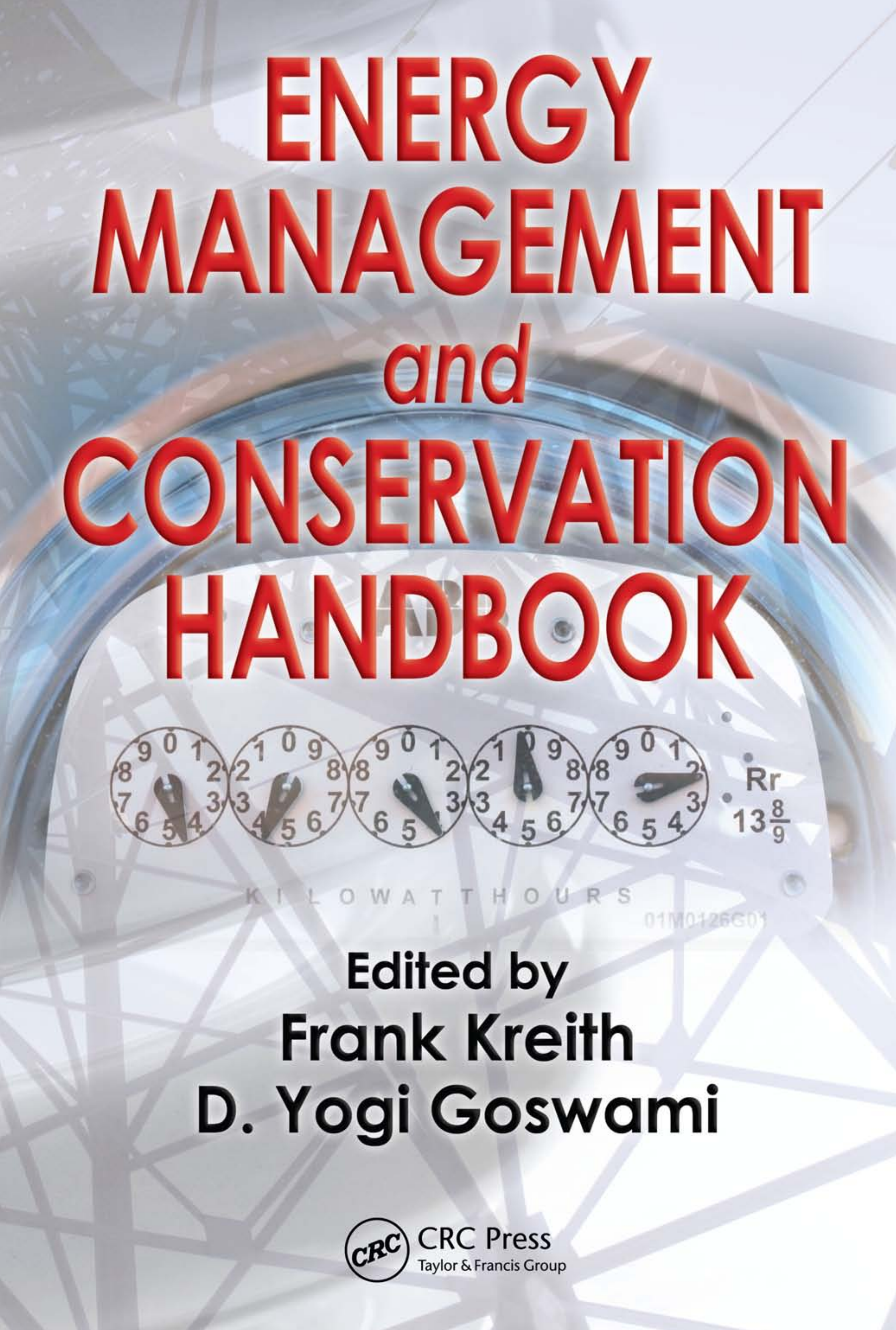

ENERGY MANAGEMENT *and* CONSERVATION HANDBOOK

Edited by
Frank Kreith
D. Yogi Goswami

CRC Press
Taylor & Francis Group

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and
CONSERVATION HANDBOOK

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Preface

Energy is universally acknowledged to be the mainstay of an industrial society. Without an adequate supply of energy, the stability of the social and economic order, as well as the political structure of a society is in jeopardy. As the world supply of inexpensive, but nonrenewable, fossil energy sources decreases, the need for energy conservation as well as for developing renewable technologies becomes ever more critical.

Recently, the issue of energy efficiency and conservation emerged as a serious challenge because it was recognized that burning of fossil fuels is one of the main contributors to global warming. Global warming is largely the result of the emission of radiation-trapping gases, such as carbon dioxide and methane, into the atmosphere. It is now the consensus of the scientific community that artificial CO_2 pollution is largely responsible for the increase in the average global temperature. Improving energy efficiency and conservation in the use of fossil fuels is therefore an important challenge for the engineering community.

This book presents some of the most important tools in the field of energy conservation. The first chapter presents projections on energy supply, demand, and cost from the International Energy Agency. The second chapter presents methods for estimating the economics of various energy conservation technologies. The next three chapters deal with procedures for ascertaining energy conservation potential in buildings. Then specific tools for energy conservation by more efficient lighting, improved appliances, and HVAC design and control are presented. One of the following chapters is devoted to heat pumps and another to electric motors. And the final two chapters deal with energy storage and demand side management.

Energy conservation measures are generally the least expensive means of reducing energy consumption and thereby ameliorating adverse environmental impacts. It is hoped that bringing the tools for energy conservation under one roof will be useful to engineers in designing and building energy-efficient systems for residential and industrial applications.

The editors would like to express their appreciation to the authors of this book for their forbearance and diligence in the course of preparing their work for publication.

In a work of this type that covers such a wide variety of subjects, errors and omissions in the first edition are unavoidable. The editors would therefore appreciate feedback from the readers to rectify any errors and improve the coverage in the next edition.

Frank Kreith
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1

Introduction to Energy Management and Conservation

Frank Kreith
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1.1 Introduction

Since the early days of the Industrial Revolution, when natural resources began to be intensively used in the production process, engineers have tried to increase the efficiency with which each of the factors of production is used. Energy is one of the basic input factors of production, along with labor, capital, and materials. Historically, however, energy was a minor factor, contributing only about 5%–10% of the total cost for most of the products. Nevertheless, even at times when little attention was paid to energy efficiency, because energy costs were low, the ratio of primary energy consumption (PEC) to gross domestic product (GDP) has declined on an average of more than 1% per year in the United States. This improvement in the PEC/GDP ratio has been mainly the result of ordinary technological progress.

After the oil embargos of 1973 and 1979, both the political and the scientific communities began to pay increased attention to the opportunities for improving the efficiency of energy use. The terms "energy use efficiency" and "energy conservation" will be used interchangeably in this book, although there is a distinction between them. To some, energy conservation denotes doing without, possibly giving up amenities to save energy. Examples of energy conservation are turning down the temperature in a home during the winter, or using mass transport instead of driving a car in order to save fuel. But, when a system can produce the same result with less expenditure of energy, the term improved energy use efficiency is more appropriate. Examples include, installing a more efficient cooling system that uses less fuel while maintaining a comfortable temperature in a home, or driving the same number of miles each year with less fuel by switching to a more fuel efficient car that provides the same level of comfort, power, and safety. Conservation and energy use efficiency received support politically when U.S. President Carter referred (1977) to "conservation as the moral equivalent of war."

In the early 1970s, a group of physicists carried out a significant study under the auspices of the American Physical Society (APS) (1974) [1] that focused on the potential for energy use efficiency based on the application of fundamental science to technological innovation. This study evaluated the limits to energy efficiency on the basis of physical or thermodynamic principles, but did not consider engineering and economic limitations. The energy limits derived from this study are known as technical potentials. Since this approach did not include economic or market analyses, the projections of future energy efficiencies were optimistic in comparison with market-guided projections based on technologies and costs. Although the APS study was primarily based on theoretical considerations, it provides a framework within which subsequent energy-efficiency analysis could be conducted.

A seminal international study under the offices of the United Nations [2] concluded that "more efficient energy use is one of the main options for achieving global sustainable development for the twenty-first century." Chapter 8 of this study is entitled "Energy and End-Use Efficiency." It claims that the next 20 years will likely see energy-efficiency gains of 25%–35% in most industrial countries and more than 40% in transitional or developing economies. Dematerialization and recycling will further improve the energy use efficiency. At the global level, just 37% of primary energy is converted into useful energy; meaning that nearly two-thirds is lost. Thus, regaining part of that lost energy by improving energy efficiency is one of the main technological drivers for sustainable development worldwide. When considering the potential for increased energy efficiency, it is essential to distinguish between several types of potential, each describing future technological achievements with different time horizons and boundary assumptions. This chapter focuses on improvements that are based on known technologies, expected costs, consumer behavior, market penetration rates, and policy measures. The International Energy Agency [3] proposed the following definitions:

- *Theoretical potential* represents achievable energy savings under theoretical considerations of thermodynamics as estimated by the American Physical Institute [1].
- *Technical potential* represents achievable energy savings that result from implementing the most energy efficient commercial and near commercial technologies available at a given time, regardless of economic consideration.
- *The market trend potential* is the efficiency improvement that can be expected to be realized for a projected year and given set of boundary conditions, such as energy prices, consumer preferences, and energy policies.
- *The economic potential* is the energy savings that would result if all replacements, retrofits, and new investments in the energy sector were shifted to the most energy efficient technologies that are cost effective at a given energy market price. The economic potential implies a well-functioning market with competition between investments in energy supply and demand.
- *The societal potential* represents "cost-effective" savings when all externalities are taken into account. These include cost from health impact, air pollution, global warming, and other ecological impacts for society.

The following estimates are based on the economic potential for improving energy use efficiency. There have been numerous studies that are all referenced and discussed in the United Nations' analysis [2]. The summary of the economic energy-efficiency potentials in North America up to the year 2010 are shown in Table 1.1. It is apparent that the greatest energy savings potential is in the transportation industry, followed by residential heating. The sources in the right-hand column refer to references in the United Nations Study. In addition to the items cited in Table 1.1, it is believed that large energy savings are possible in office equipment, such as computers and communication. A similar estimate for the economic energy-efficiency potential for Western Europe for the years 2010 and 2020 is presented in Table 1.2, where the resource references refer to the bibliography in Ref. 2. Similar estimates for the energy saving potential in Japan, Asia, and Latin America are presented in Ref. 2.

TABLE 1.1 Economic Energy Efficiency Potentials in North America, 2010

	Economic Potential (%)				
Sector and Area	United States[a]	Canada	Energy Price Level Assumed	Base Year	Source
Industry					
Iron and steel	4–8	29	United States: scenario for price developments[b]	United States: 1995	United States: Interlab (1997), Brown and others (1998), and Romm (1999)
Aluminum (primary)	2–4				
Cement	4–8				
Glass production	4–8			Canada: 1990	
Refineries	4–8	23	Canada: price scenario by province[c]		Canada: Jaccard and Willis (1996) and Bailie and others (1998)
Bulk chemicals	4–9	18			
Pulp and paper	4–8	9			
Light manufacturing	10–18				
Mining	n.a.	7			
Industrial minerals	n.a.	9			
Residential					
Lighting	53		United States: scenario for price developments	United States: 1995	United States: Interlab (1997), Brown and others (1998), and OTA (1992)
Space heating	11–25				
Space cooling	16				
Water heating	28–29			Canada: 1990	
Appliances	10–33		Canada: price scenario		Canada: Bailie and others (1998)
Overall		13			
Commercial and public					
Space heating	48		United States: scenario for price developments	United States: 1995	United States: Interlab (1997) and Brown and others (1998)
Space cooling	48				
Lighting	25				
Water heating	10–20			Canada: 1990	
Refrigeration	31		Canada: price scenario		Canada: Bailie and others (1998)
Miscellaneous	10–33				
Overall	n.a.	9			
Transportation					
Passenger cars	11–17		United States: scenario for price developments	United States: 1997	United States: Interlab (1997) and Brown and others (1998)
Freight trucks	8–9				
Railways	16–25				

(continued)

TABLE 1.1 (***Continued***)

	Economic Potential (%)				
Sector and Area	United States[a]	Canada	Energy Price Level Assumed	Base Year	Source
Aeroplanes	6–11			Canada: 1990	
Overall	10–14	3	Canada: price scenario		Canada: Bailie and others (1998)

[a] Industrial energy efficiency potentials in the United States reflect an estimated penetration potential under different conditions based on the Interlaboratory Working Group on Energy Efficient and Low-Carbon Technologies (1997). There are no separate estimates available for the economic potential. The economic potential under *business-as-usual* fuel price developments is estimated at 7% in energy-intensive industries and 16% in light industries.

[b] The Inter-Laboratory Working Group study (1997) used price scenarios for 1997–2010 to estimate the potential for energy efficiency improvement, based on the *Annual Energy Outlook 1997* scenario (EIA 1996). The scenario assumes a 1.2% annual increase in oil prices from 1997 levels.

[c] For comparison; in 2010 light fuel oil prices are $6–$8 a gigajoule at the 1999 exchange rate (Jaccard and Willis Energy Services 1996).

TABLE 1.2 Economic Energy Efficiency Potentials in Western Europe, 2010 and 2020

	Economic Potential (%)[a]				
Sector and Technological Area	2010	2020	Energy Price Level Assumed	Base Year	Source
Industry					
Iron and steel, coke ovens	9–15	13–20	1994	1995	Jochem and Bradke (1996) and Ameling and others (1998)
Construction materials	5–10	8–15	1997	1997	
Glass production	10–15	15–25	1997	1997	ATLAS (1997)
Refineries	5–8	7–10	1995	1997	Refining Processes (1998)
Basic organic chemicals	5–10		1997	1996	Patel (1999) and Brewer and Lopez (1998)
Pulp and paper		50	1996	1997	De Beer (1998)
Investment and consumer goods	10–20	15–25	1994	1995	Jochem and Bradke (1998) and Böde and others (1999)
Food	10–15		1997	1997	Jochem and Bradke (1996)
Cogeneration in industry		10–20	1997	1997	ATLAS (1997) and EC (1999)
Residential					
Existing buildings					
Boilers and burners	15–20	20–25	Today’s prices	1997	ETSU (1994) and Böde and others (1999)
Building envelopes	8–12	10–20	Today’s prices	1995	Ziesing and others (1999)
New buildings		20–30	Today’s prices	1995	Altner, Durr, Michelson (1995)
Electric appliances	20–30	35–45	1997	1997	GEA (1995), ECODROME (1999), Hennicke and others (1998), and Boardman and others (1997)
Commercial, public, and agriculture					
Commercial buildings	10–20	30	8–13 cts/kWh	1995	Geiger and others (1999)
Electricity	10–25	20–37	4–10 cts/kWh	1997	ECODROME (1998)

(continued)

TABLE 1.2 (***Continued***)

Sector and Technological Area	Economic Potential (%)[a] 2010	2020	Energy Price Level Assumed	Base Year	Source
Heat		15–25	Today's prices	1998	Zeising and others (1999)
Public buildings		30–40	7–15 cts/kWh	1992	Brechbühl (1992)
Agriculture and forestry		15–20	Today's prices		Neyer and Strebel (1996)
Horticulture		20–30	Today's prices		Arbeitsgemeinschaft (1992)
Decentralized cogeneration		20–30	Today's prices	1995	Ravel (1994)
Office equipment		40–50	1995	1995	Aebischer and others (1996), MACEBUR (1998), and Hallenga and Kok (1998)
Transportation					
Cars	25		Today's prices	1995	IPSEP (1995)
Door-to-door integration	4			1995	Zeising and others (1999)
Modal split of freight transport		3[b]		1995	
Trains and railways		20	Today's prices	1999	Brunner and Gartner (1999)
Aircraft, logistics	15–20	25–30	Today's prices	1998	IPCC (1999a)

[a] Assumes a constant structure or use of the sector or technology considered.
[b] Refers to the final energy use of the entire sector.

The globalization of many industrial sectors creates enormous potential for improving energy efficiency on a global scale. For example, among the developing countries Mexico implemented a large-scale energy efficient lighting program for the residential sector. Funded by the Mexican Electricity Commission and other donors between 1995 and 1998 about 1 million compact fluorescent lamps were sold in the areas covered by the program. Use of the lamps avoided 66 MW of peak capacity and resulted in monthly energy savings of 30 GWh.

If energy-efficiency improvement and energy conservation in the United States were perused vigorously and consistently with realistic energy price signals, the total cumulative total energy savings from higher energy-efficiency standards for residential and commercial equipment that would be effective in the years 2010–2030 amounts to just under 26 quads [4]. Annual savings amounting to one and a half and three quads in 2025 have been estimated by Lawrence Berkeley National Laboratory (LBL) and American Council for an Energy-Efficient Economy (ACEE), respectively, for improved appliances [5]. An additional savings potential from improved building technologies amounting to 4 quads/year has been estimated to be possible for 2025 by the commission on Energy Policy. The largest energy savings are associated with standards for residential electronic products followed by higher efficiency standards for commercial refrigeration, lighting, and air conditioning. The next largest savings in the residential sectors could come from higher standards for electric water heaters and lighting [4].

In the U.S. achieving this savings potential could increase national energy security and help to improve the nation's international balance of payments. Hence, improving energy efficiency across all sectors of the economy is an important national objective [5]. However, it should be noted that free market price signals may not always be sufficient to effect energy efficiency. Hence, legislation on the state and/or national level for energy-efficiency standards for equipment in the residential and commercial sector may be necessary. There is a considerable debate whether incentives or mandates are the preferred way to improve energy efficiency. Such measures may be necessary because national surveys indicate that consumers consistently rank energy use and operating costs quite low on the list of attributes they consider when purchasing an appliance or while constructing a building. Incentives may be the preferred option provided they induce decision makers to take appropriate action. Unfortunately, in the case of buildings and appliances, the long-term economical benefits of conservation do not rank as high as the initial investment costs. Hence, to achieve increased energy efficiency, mandates may be necessary. Mandates are politically acceptable when the required actions are inexpensive, non-controversial, and simple to perform. When properly enforced, mandates have predictable results and may be the preferred method of achieving energy efficiency.

Every energy conservation measure requires an upfront capital investment and given usual economic constraints, the initial costs of an energy conservation measure is very important. One of the criteria by which to judge an energy conservation measure is its benefit to cost ratio.

There are two aspects to the benefit to cost ratio of energy conservation: one is the ratio of the total value of British thermal units (BTUs) or kilowatt hours (kWh) saved during the lifetime of the system to the total system cost (investment, operating, and maintenance); the other is the value of yearly net energy savings (i.e., the difference between the energy saved and the energy used for operation and maintenance) divided by the annual levelized cost of the capital equipment.

When the value of the saved energy and the cost of installing conservation measure are known, the simple payback period (PP) can be calculated from [6]:

$$\mathrm{PP} = \frac{\text{Cost of installation in \$}}{\text{Net value of energy saved per year (\$/year)}}$$

The net value of the saved energy equals the amount of energy saved times the cost per unit of the energy (dollars/BTU or dollars/kWh). This approach is acceptable for preliminary estimates if the PP is short, say less than 4 years. For a more precise estimate, the time value of money, the inflation rate, and the escalation in fuel costs must be considered as shown in Chapter 3.

By the year 2004, national efficiency standards were in effect for a variety of residential and commercial appliances. Updated standards will take effect in the next few years for several more products. Outside the

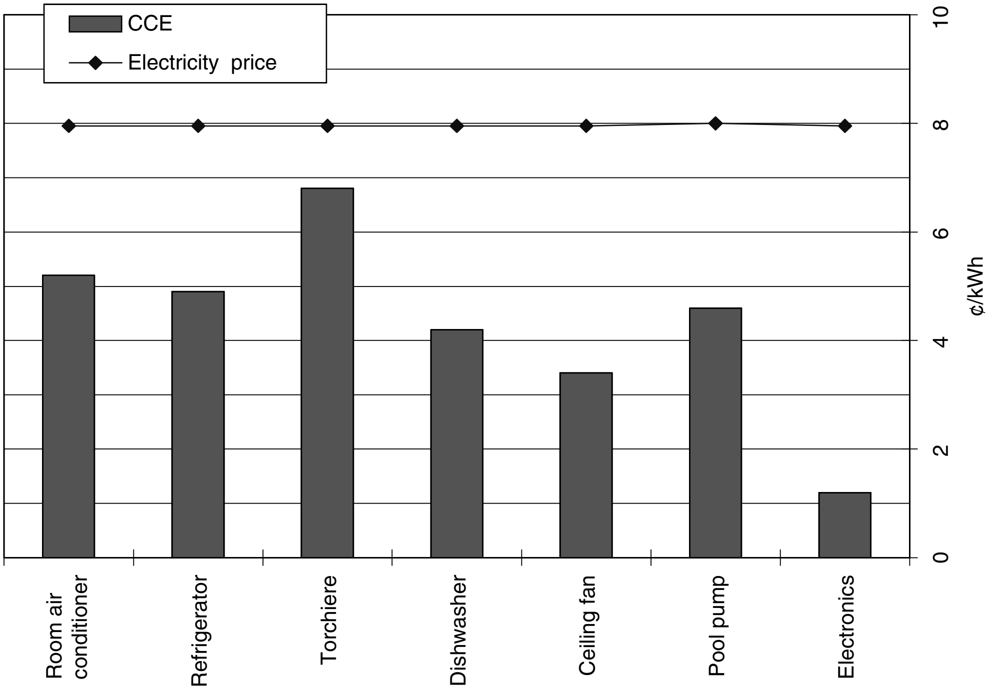


FIGURE 1.1 Comparison of cost of conserved energy for 2010 Standards to projected electricity price in the residential sector.

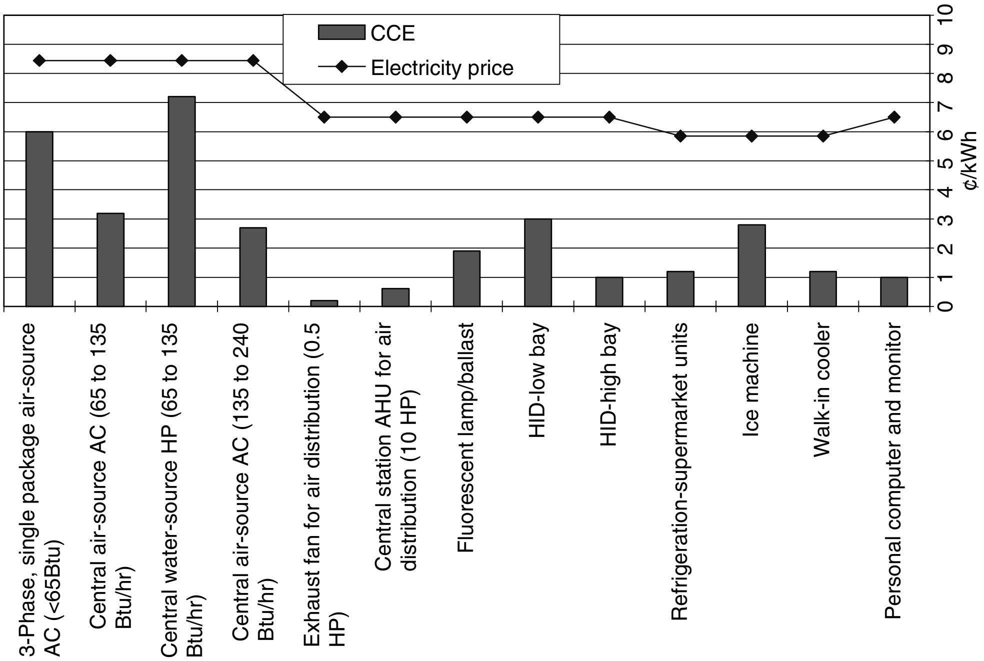


FIGURE 1.2 Comparison of cost of conserved energy for representative 2010 Standards to marginal electricity price in the commercial sector. (1 Btu = 1055 J.)

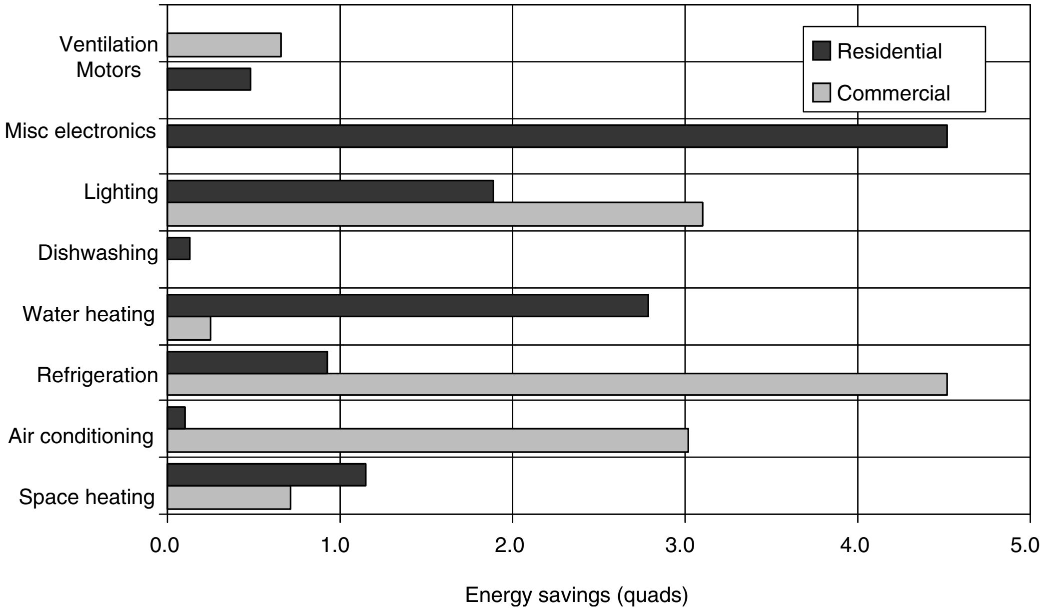


FIGURE 1.3 Cumulative primary energy savings from upgraded standards for products installed in 2010–2030 period. (1 quad = 1.055×10^{18} J.)

United States, over 30 countries have adopted minimum energy performance standards. A study conducted for the U.S. National Commission on Energy Policy in 2004 estimated the national impact of new and upgraded energy standards for residential and commercial equipment [4].

The results of this study indicated that the cost of conserved energy for the proposed 2010 standards are well below the relevant energy prices for most products as shown in Figure 1.1 for equipment in the residential sector and in Figure 1.2 for equipment in the commercial sector. Thus, most of the new standards for improving energy efficiency would be cost effective. Figure 1.3 shows the cumulative primary energy savings that could be attained in the U.S. by upgrading efficiency standards for such equipment installed in the 2010–2030 period in the residential and commercial sectors.

1.2 Barriers to Energy Conservation

Traditional energy prices are understated because they do not include the health, social, and environmental costs of using fuels. For example, gasoline prices do not take into account the costs associated with military requirements to protect access to oil sources, global warming, acid rain, and adverse health effects. This is an institutional barrier to increasing energy efficiency. Some of the key barriers to achieving increased efficiency are listed below.

1.2.1 Lack of Objective Consumer Information

Efficiency claims in the market place are often made by competing manufacturers, without an objective third party to evaluate the actual efficiency claims.

1.2.2 Failure of Consumers to Make Optimal Energy-Efficiency Decisions

Consumers often choose the least expensive appliance, rather than the appliance that will save them money over the long term; consumers are also often confused about efficiency ratings and efficiency improvements.

1.2.3 Replacement Market Decisions Based on Availability Rather Than Efficiency

Decisions concerning replacement of worn out or broken equipment are made without energy efficiency as a high priority. Usually, the primary concern for the consumer is restoring service as quickly as possible. This requires buying whatever equipment the plumbing or heating contractor may have on hand.

1.2.4 Energy Prices do not Take into Account the Full Environmental or Societal Costs

External costs associated with public health, energy production, global warming, acid rain, air pollution, energy security, or reliability of supply are usually ignored.

1.2.5 Competition for Capital to Make Energy-Efficiency Investments

Energy-efficiency investments in the commercial and industrial sectors often must compete with other business investments; therefore, efficiency investments with a payback of more than 3 years are avoided.

1.2.6 The Separation of Building Ownership from Utility Bill Responsibility

Renters will rarely make energy-efficiency investments in buildings that they do not own, especially when the utilities are included in the rent.

1.2.7 Commercial Buildings and Retail Space are Usually Built on Speculation with Low First-Cost a Priority

The building's long-term operation cost, which is usually paid by the tenant(s) rather than the owner, is not important to the speculator/builder.

Overcoming these barriers may require legislation on the state and/or federal level. This type of legislation is likely to be more successful if it considers criteria, such as fiscal fairness, probability of success, and ease of implementation in addition to the economic benefits that will eventually ensue. This book presents energy-efficient technologies for electric motors, lighting, home appliances, and space conditioning which offer the potential for substantial energy conservation in the near future according to experts to their respective fields.

Important energy management tools for utilities and energy planners to achieve energy efficiency are integrated resource planning (IRP) and demand side management (DSM). Integrated resource planning is the process of simultaneously examining side-by-side all energy savings and energy-producing options to optimize the mixture of resources and minimize the total costs. Considerations of environmental and health costs can be including. Demand side management is a broad term that encompasses the planning and implementation of utility sponsored programs that influence the amount or timing of customers' energy use. There are four basic techniques for influencing and reducing energy use [7]:

- Peak clipping, a reduction in the system peak loads;
- Valley filling, the building of off-peak loads;

TABLE 1.3 Load Impacts of Conservation Technologies

	Loadshape Impacts			
Technology	Peak Clip	Valley Filling	Load Shift	Strategic Conservation
Building Envelope				
Roof and wall insulation				X
Double glazed windows				X
Passive solar/solar films	X			X
Infiltration/exfiltration				X
Lighting				
Low wattage fluorescent	X			X
High efficiency ballasts	X			X
Daylighting controls/reflectors	X			X
Heating/Ventilation/Motors				
Heat pumps				X
Gas absorption chillers	X	X		X
Exhaust air heat recovery				X
High efficiency motors	X			X
Appliances and Water Heating				
High efficiency A/C	X			X
Tank insulation				X
Solar water heater	X			X
Load management				
Water heater cycle controls		X	X	
Timers			X	X
Radio controlled central A/C	X		X	
Thermal storage	X	X	X	
Programmable thermostats				X
Refrigeration				
High efficiency compressors	X			X
Automatic defrost controls	X			X
Pipe and tank insulation				X

TABLE 1.4 Estimated Paybacks of Energy Conservation Technologies

Technology	Installed Cost $	Energy Savings (kWh/yr)	Cost Savings ($/yr)	Simple Payback (yr)	Life (yr)	Cost of Saved Energy (c/kWh)
Building Envelope						
Insulation						
Wall	800	2831	226	1.2–4.6	50	1.90
Ceiling	1140	4916	393	1–3.8	50	1.56
Foundation	648	2880	230	2.1–8.4	50	1.51
Windows, double pane, low-E,N	2.75/SF	6.3/SF	0.51/SF	5.4	20	2.93
Windows, double pane Low-E,S	2.75/SF	4.5/SF	0.40/SF	6.9	20	3.42
Glass storm window	5/SF	9.5/SF	0.76/SF	4.6–10.6	20	3.54
Solar films	1.85/SF	4.75/SF	0.38/SF	4.8	3–15	3.26–13.78
Weatherstripping/ caulking	230	1852	148	1.6	2.5	5.23
HVAC/Motors						
Repair duct leaks	110	2300–4000	184–320	0.3–0.6	7	0.61
Duct insulation	0.85/LF	2–7.5/L	0.16–0.58/LF	1.5–5.3	25	1.55
Heat pumps						
Air-source, hot climate	3920	3884	311	2.9	15	1.94
Destratification fans	415	2666	213	1.9	10	1.82
Efficient						
Air conditioners	300/ton	600/ton	48/ton	6.2	15	4.19
Heat exchangers	3760/kcfm	17000/kcfm	1190/kcfm	3.1	20	1.49
Direct						
Evaporative cooling	850/ton	1241/ton	87/ton	2.35–20	1.08–3.51	
EMCS	300	2790	195	1.5	10	1.26
Economizer	62.5	162–1785	11.5–125	0.5–5.5	15	2.38
Efficient motors (1–5 hp)	166	520	—	1.3	7	5.12
Optimum motor sizing	192	—	53	3.6	7	—
Appliances and Water Heating						
Heater wrap	21	273	19.11	1.1	10	0.90
Thermal traps	8	380	30	0.3	15	0.25
Pipe wrap	5	20	1.60	3.1	10	2.93
Low-flow shower head	9	275	22	0.4	10	0.38
Heat-pump						
Water heater	1350	2780	222	4.7	13	3.50
Heat-recovery						
Solar hot water heater	700	1100	88	7.9	13	5.98
Low flow system	42/SF	81/SF	6.50/SF	6.5	20	3.49
Refrigerators and freezers	731	590	47.2	1.3	20	0.68
Low-water						
Washing machine	150	480	38.4	3.9	15	2.62
Cook tops	302	44	3.52	0.6	18	0.33
Ovens	215	103	8.24	1.8	18	1.06
Lighting						
Efficient incandescent	1.13	8	0.48	469 (hr)	750 (hr)	6.84
Compact fluorescent	13	57	5.67	2150 (hr)	10000 (hr)	2.44

(continued)

TABLE 1.4 (***Continued***)

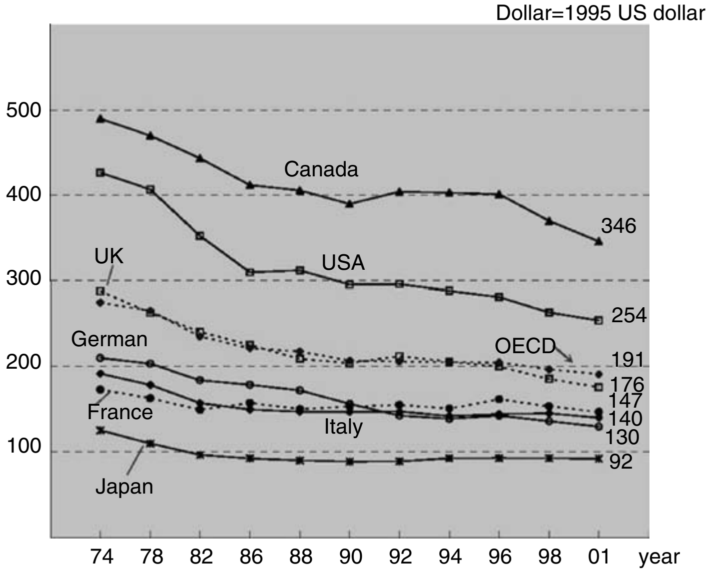
Technology	Installed Cost $	Energy Savings (kWh/yr)	Cost Savings ($/yr)	Simple Payback (yr)	Life (yr)	Cost of Saved Energy (c/kWh)
High efficiency						
Fluorescent	18	153	9.3	0.9	20000 (hr)	2.42
Exit light						
Conversion kits	39	289	29.36	1.32	10000 (hr)	2.67
Photocell	12	219	17.52	0.7	5	1.20

Low-E, low emissivity coating on glass; SF, square foot; LF, lineal foot; kcfm, 1000 cubic feet per minute; EMCS, energy management and control systems; hr, hour; HVAC, heating, ventilation, and air conditioning.

Source: From Kreith, F. and Burmeisth G., *Energy Management and Conservation*, NCSL, Denver, CO, 1993.

- Load shifting, involves shifting of load from on-peak to off-peak periods;
- Strategic conservation, the load shape change that results from utility stimulated programs.

Table 1.3 displays the effect of various renewable conservation measures in a DSM scheme, while Table 1.4 shows estimated payback in energy costs for conservation technologies. A novel method of utilizing excess production capacity and level, the electric power consumption was recently proposed by the Electric Power Research Institute (EPRI) [8]. According to EPRI, consumer demand for electricity peaks during the day, but more than 40% of the generating capacity in the United States is idle or generating at reduced load overnight. If the transportation system were to use plug-in hybrid vehicles,



Source IEA/Energy balances of OECD countries (2000–2001)

FIGURE 1.4 Relative comparison of energy intensities.

most of these vehicles could be charged during off-peak hours. Chapter 13 presents more details on DSM as well as discussions of successful DSM programs.

Increases in energy use efficiency have made impressive contributions to both the economy and the environment in the United States since the 1970s [2]. But, as shown in Figure 1.4, the energy use efficiency in other countries has consistently been superior to that in North America and the rate of improvement in energy efficiency in the United States has slowed, largely as a result of low energy prices and lack of political interest until recently. About 10 years ago, it was estimated that the U.S. economy had become considerably more energy efficient, using only about three-quarters as much energy as it would have if the growth trends of the 1960s and 1970s had continued while energy services and economic output also continued to grow [9].

The issue of energy efficiency re-emerged as a serious challenge about 10 years ago, when it was recognized that the burning of fossil fuels is one of the main contributors to global warming and that global oil production will reach a peak within 10–20 years and then begin to decline [10].

Ever since petroleum geologist M. King Hubbert correctly predicted in 1956 that U.S. oil production would reach a peak in 1973 and then decline, scientists and engineers have known that world-wide oil production would follow a similar trend. Today, the only question is when the world peak will occur.

The U.S. transportation system depends almost entirely (approximately 97%) on oil and foreign imports have risen steadily since 1973 as the demand increased and domestic supplies decreased. Today, more than 60% of U.S. oil consumption is imported and the dependence on foreign oil is bound to increase. There is no question that once the world peak is reached and oil production begins to drop, either alternative fuel will have to be supplied to make up the difference between demand and supply, or the cost of fuel will increase precipitously and create an unprecedented social and economic crisis for our entire transportation system.

Among energy analysts, the above scenario is not in dispute. There is, however, uncertainty about the timing. Bartlett [11] has developed a predictive model based on a Gaussian curve similar in shape to the data used by Hubbard as shown in Figure 1.5. The predictive peak in world oil production depends only on the assumed total amount of recoverable reserves. According to a recent analysis by the Energy Information Agency world ultimately recoverable oil reserves are between 2.2×10^{12} and 3.9×10^{12} barrels (bbl) with a mean estimate of the U.S. Geological Survey (USGS) at 3×10^{12} bbl. But, changing the total available reserve from 3×10^{12} to 4×10^{12} bbl increases the predicted time of peak production by

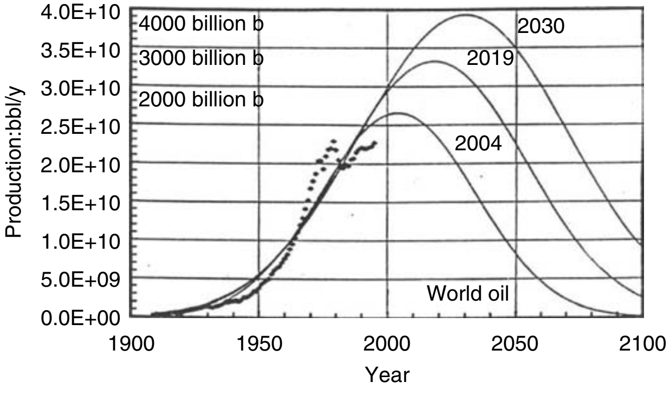


FIGURE 1.5 World oil production vs. time for various amounts of ultimate recoverable resource. (From Bartlett, A. A., *Math. Geol.*, 32, 2002.)

merely 11 years, from 2019 to 2030. The present trend of yearly increases in oil consumption, especially in China and India, shortens the window of opportunity for a managed transition to alternative fuels even further. Hence, irrespective of the actual amount of oil remaining in the ground, peak production will occur soon and the need for starting to supplement oil as the primary transportation fuel is urgent because an orderly transition to develop petroleum substitutes will take time and careful planning.

Global warming is largely the result of the emission of radiation trapping gases, such as CO_2 and CH_4 (carbon dioxide and natural gas) into the atmosphere [12]. Combustion of fossil fuels results inevitably in generation of CO_2, which is then trapped in the atmosphere and absorbs infrared radiation emitted from the earth's surface. Figure 1.6 shows the atmospheric CO_2 concentration as a function of time. Beginning with the industrial revolution, CO_2 concentration has increased

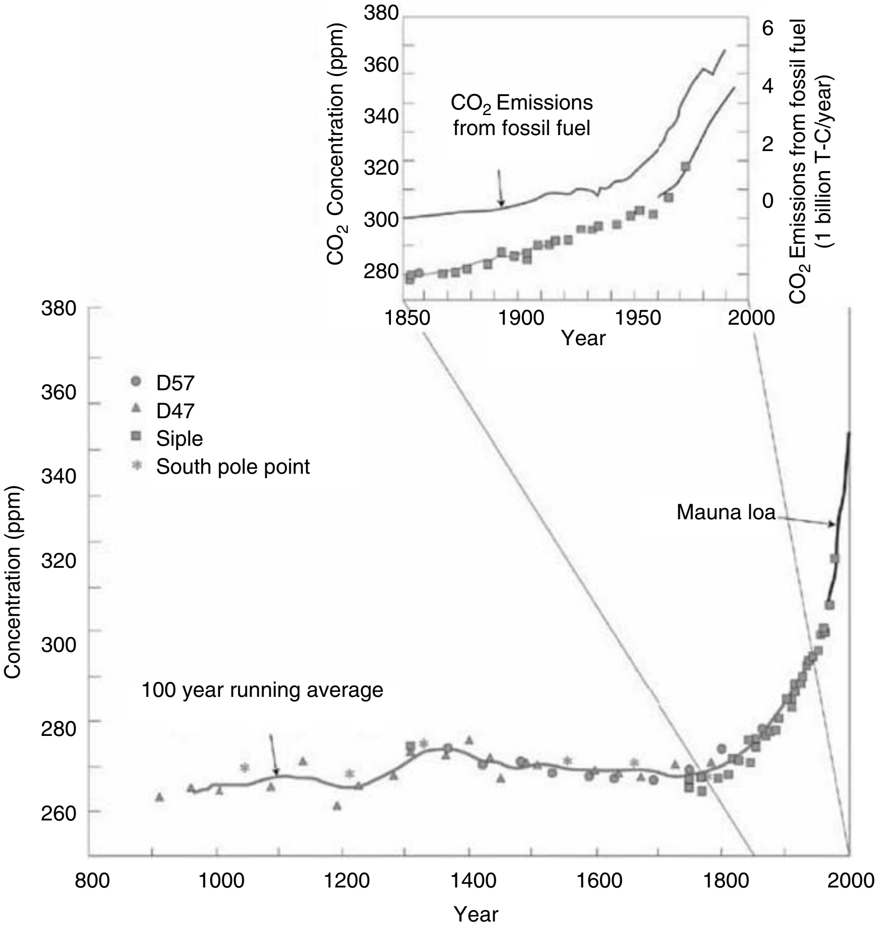


FIGURE 1.6 Increase of the carbon dioxide level and changes in fossil energy consumption. *Note:* This chart is prepared from the data of CO_2 concentration level of the past millennium based on the ice sheet core records at the D47, D57, Siple Station, and the South Pole, and the CO_2 levels since 1958 that are measured at Mauna Loa Observatory in Hawaii. Ice sheet cores were all collected on the Antarctic Continent. The smooth curve is a 100-year running average. The sharp rise of the CO_2 level since the outset of the Industrial Revolution is evident, going along with the increase of CO_2 emissions originating from the use of fossil fuels. From IPCC (1995) International panel on climate change, White Paper on Environment, 2000.

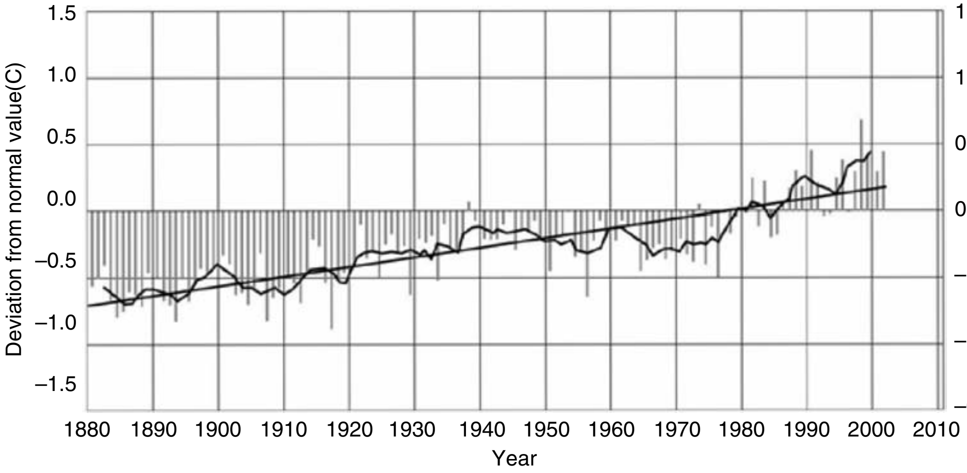


FIGURE 1.7 Transition of deviation from normal surface temperature. *Note:* Bars represent the temperature of each year; lines show 5-year running average and straight lines stand for long-term trend. From IPCC (1995) and White Paper on the Environment 2002 (Japanese Missing for the Environment).

exponentially and it is now the consensus of the scientific community that man-made CO_2 pollution is largely responsible for the increase in the average global temperature shown in Figure 1.7. The United States produces about one-quarter of the global CO_2 emission, as shown in Figure 1.8, and the per capita CO_2 emission in North America is more than five times that of the global average, as shown in Figure 1.9. Since, at present, the energy sources in which the U.S. economy is based, are mostly fossil fuels, namely petroleum, natural gas, and coal, with relatively modest contributions from hydropower and nuclear energy, it is apparent that improving energy use efficiency in North America would have to be a key factor in any effort to reduce and eventually eliminate global warming. The goal of this handbook is to provide engineers and energy planners with the tools necessary to improve

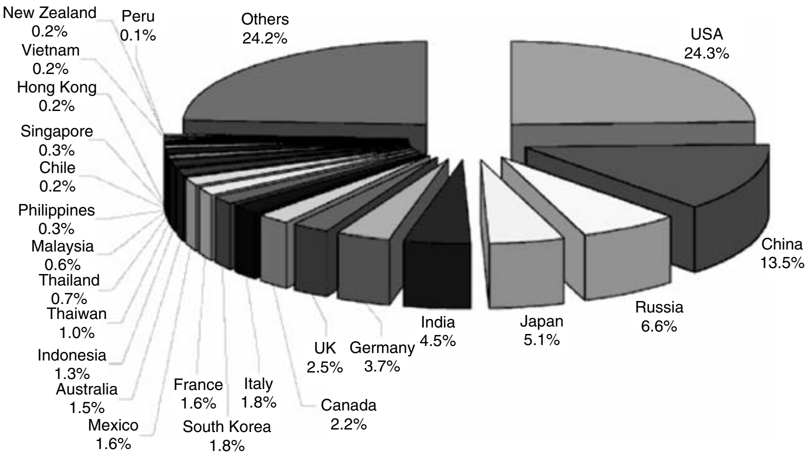


FIGURE 1.8 CO_2 emissions by Country (2001). (Prepared from the EDMC Handbook of Energy and Economic Statistics in Japan (2004).

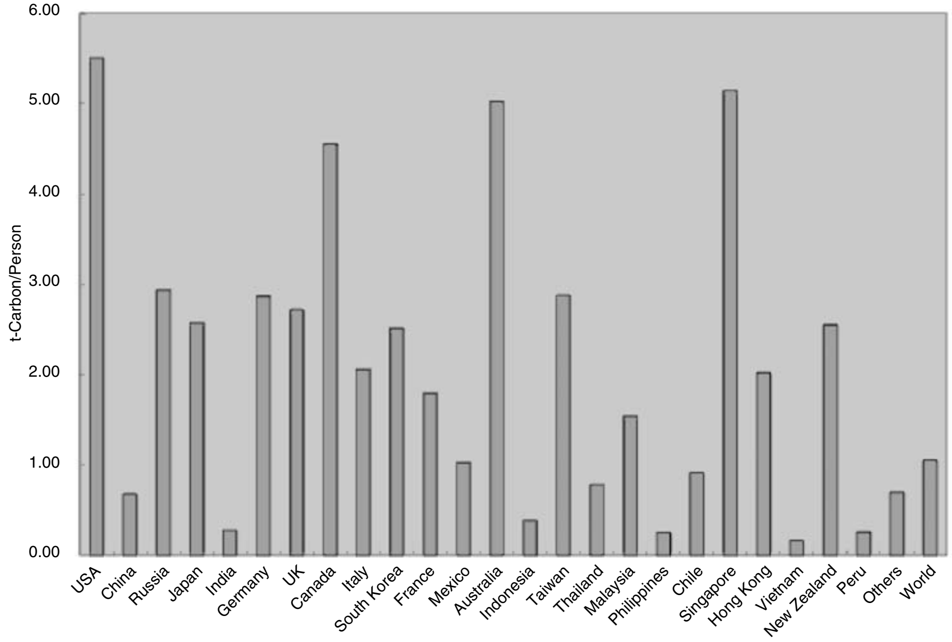


FIGURE 1.9 Per-capita CO_2 emissions (2001). (Prepared from the EDMC Handbook of Energy and Economic Statistics in Japan (2004).

energy management leading to higher energy end use efficiencies in buildings, industry, and transportation.

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2

Outlook for U.S. Energy Consumption and Prices in the Midterm

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2.1 Introduction

All projections of energy-economic systems, particularly those that incorporate consumer and producer behavior, are inherently uncertain. However, consumer and producer behavior are not the only sources of uncertainty. Some of the other critical uncertainties on which projections depend include:

- The rate of technological progress for end use and supply technologies
- Changes in energy market regulations and efficiency standards
- The quantity, location, and depth of energy resources in the ground (e.g., coal, crude oil, natural gas, nuclear material)
- The costs to explore, locate, and ultimately produce energy resources
- The willingness of financial markets to make energy investments

Consequently, the projections described in this chapter are not statements of what will happen, but rather statements of what might happen given the assumptions and methodologies used.

The outlook of U.S. energy markets through 2025, as presented in this chapter in Section 2.1 through Section 2.9, was developed using the Energy Information Administration's (EIA) National Energy Modeling System (NEMS) [1]. With the exception of higher world oil prices, the October oil futures case projection uses the assumptions of the *Annual Energy Outlook 2005 (AEO2005)* reference case [2]. The reference case projection for *AEO2006* is available on the EIA Internet website.* Central to this scenario is the assumption that current technological and demographic trends and current laws and regulations will continue as usual into the future. The October oil futures case of *AEO2005* assumes that crude oil (using the imported refiner's acquisition cost (IRAC)), in real 2003 dollars, is almost $5 per barrel higher than the *AEO2005* reference case in 2025.†

The EIA does not propose, advocate, or speculate on future legislative or regulatory changes. Thus, the *AEO2005* projections, including the October oil futures case described in this chapter, provide a policy-neutral basis that can be used as an adjunct to analyze policy initiatives. For scenarios based on alternative macroeconomic growth rates, world oil prices (both higher and lower than those used in this outlook) or alternative rates of technological progress, the reader is encouraged to review the alternative scenarios developed in the *AEO2005* [3].

2.2 Key Energy Issues to 2025

World crude oil prices—defined by the U.S. average imported refiner's acquisition cost of crude oil (IRAC)—reached a recent low of $10.29 per barrel (in 2003 dollars) in December 1998. For the next three years, crude oil prices ranged between just under $20 and just over $30 per barrel. Since December 2001, however, prices have steadily increased to about $46 per barrel in October 2004 and into the mid-$60 dollar per barrel range in the second half of 2005.

Strong growth in the demand for oil worldwide, particularly in China and other developing countries, is generally cited as the driving force behind the sharp price increases seen over the 2002–2005 period. Other factors contributing to the upward world oil price trend include a tight supply situation that has shown only limited production response by countries outside of the Organization of Petroleum Exporting Countries (OPEC) to higher prices; changing views on the economics of oil (and gas) production; and concerns about economic and political situations in the Middle East, Venezuela, Nigeria, China, and the former Soviet Union. However, the rate of technological progress, new international emission control protocols such as the Kyoto Protocol and significant global concerns about the security

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*http://www.eia.doe.gov/oiaf/aeo/index.html. See http://www.eia.doe.gov/oiaf/aeo/assumption/pdf/0554(2005).pdf for a detailed description of the assumptions of the *AEO2005* reference case.

†The outlook and commentary described herein represent solely the views of the author and not necessarily the views of EIA, the U.S. Department of Energy, the administration, or any agency of the U.S. government.

of the petroleum supply represent additional factors that may trigger actions that reduce the upward pressure on crude oil prices, i.e., by increasing production from previously unexpected or uneconomic sources or by reducing petroleum demand. For example, technological progress may lead to cost reductions for gas-to-liquids and coal-to-liquids technologies, the development of new methods and technologies to economically develop domestic oil shale resources that are currently plentiful but uneconomic, and the discovery of significant new ‘finds’ of crude oil in other relatively unexplored regions of the world. The future path of world oil prices is a major uncertainty facing world oil markets.

The October oil futures case was based on the October 2004 prices from the New York Mercantile Exchange (NYMEX) futures market (corrected for the difference between futures prices and the IRAC). The NYMEX crude oil outlook implies that the annual average price in 2005 will exceed the 2004 average price level, and that prices will then decline only slowly in constant 2003 dollars over the next five years, resulting in a 2010 price of about $31 per barrel.* The IRAC is then projected to rise to about $35 per barrel by 2025.

From 1986 to 2000, when U.S. natural gas consumption grew from 16.2 trillion ft.^{3} to a high of 23.3 trillion ft.^{3}, 40% of the increased demand was met by imports, predominantly from Canada. Based on EIA’s assessment of recent data and recent projections by Canada’s National Energy Board, EIA has revised expectations about Canadian natural gas production, particularly coalbed methane and conventional production in Alberta. It is unlikely that future production from Canada will be able to support a continued increase in U.S. imports.

In the October oil futures case, U.S. natural gas consumption is projected to grow from 22 trillion ft.^{3} in 2003 to over 30.5 trillion ft.^{3} in 2025. Most of the additional supply is expected to come from Alaska and imports of liquefied natural gas (LNG). A key issue for U.S. energy markets is whether the investments and regulatory approvals needed to make those natural gas supplies available will occur. The following sections summarize the key trends in the projection. A summary of the projection is provided in Table 2.1.

2.3 Economic Growth

The output of the Nation’s economy, measured by gross domestic product (GDP), is projected to grow by 3.1% per year between 2003 and 2025 (with GDP based on 2000 chain-weighted dollars). Figure 2.1 shows the trend in the annual real growth for GDP, including the projection. The labor force is projected to increase by 0.9% per year between 2003 and 2025. Labor productivity growth in the nonfarm business sector is projected to be over 2.0% per year.

Compared with the second half of the 1990s, the rates of growth in GDP and nonfarm employment were lower from 2000 through 2002. Economic growth has been more robust since 2003. Real GDP growth was 3.0% in 2003 and 4.4% in 2004. Total population growth (including armed forces overseas) is expected to remain fairly constant after 2003, growing by 0.8% per year on average. Labor force growth is expected to slow as a result of demographic changes, but more people over 65 are expected to remain in the work force. Nonfarm business productivity growth has been strong recently, averaging 3.8% per year from 2000 to 2003. Productivity growth from 2003 to 2025 is expected to average about 2% per year, supported by investment growth of about 5.0% per year.

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*There are large oil projects world-wide that are scheduled to come on line between 2008 and 2009 which should increase supply; the high world oil prices will dampen world petroleum demand. Between the lower demand resulting form higher prices and the increased supply which is in response to the higher prices, we should see a dip from current prices, unless you expect to see continued or increasing war fears and global instability. There is no question that the current situation with the potential for war-generated supply disruptions could send prices into the $100–$200 per barrel range for a while. I don’t consider that situation "normal." If such instability is sustained another 2–3 years, the situation could become part of the "normal" view and then I would be inclined to agree on the higher prices. So if one believes that the current level of fear and instability that the world will face in the next 25 years is likely, high sustained prices over the next 10–20 years are likely. Financial incentives to find and develop alternative technologies for petroleum substitutes and higher-efficiency end use appliances will be high and will eventually put downward price pressures latter as they significantly penetrate the market.

TABLE 2.1 October Oil Futures Case (AEO2005): Total Energy Supply and Disposition Summary (Quadrillion Btu per Year, Unless Otherwise Noted)

	2002	2003	2005	2010	2015	2020	2025	2003–2025 (%)
Primary energy production (quadrillion Btu)								
Petroleum	14.71	14.38	14.67	15.74	14.98	14.22	13.38	0.3
Dry natural gas	19.48	19.58	19.60	21.34	21.89	23.09	22.72	0.7
Coal	22.70	22.66	24.12	25.15	25.52	27.07	29.91	1.3
Nuclear power	8.14	7.97	8.31	8.49	8.62	8.67	8.67	0.4
Renewable energy	5.79	5.89	6.48	6.85	7.15	7.60	8.26	1.5
Other	1.12	0.93	1.02	1.16	0.94	0.90	0.97	0.2
Total production	71.94	71.42	74.20	78.64	79.09	81.54	83.91	0.7
Net imports (quadrillion Btu)								
Petroleum	22.64	24.10	25.64	27.15	31.23	35.09	38.96	2.2
Natural gas	3.59	3.32	3.43	4.86	6.97	7.98	8.83	4.5
Coal/other (indicates export)	0.47	0.43	0.48	0.14	0.19	0.25	0.58	N/A
Total net imports	25.75	26.99	28.55	31.87	38.39	43.32	48.37	2.7
Consumption (quadrillion Btu)								
Petroleum products	38.41	39.09	40.28	43.98	47.11	50.22	53.21	1.4
Natural gas	23.59	22.54	22.892	26.29	29.01	31.21	31.71	1.6
Coal	21.98	22.71	23.27	24.91	25.67	27.31	30.50	1.3
Nuclear power	8.14	7.97	8.31	8.49	8.62	8.67	8.67	0.4
Renewable energy	5.79	5.89	6.48	6.85	7.15	7.61	8.27	1.6
Other	0.07	0.02	0.01	0.03	0.07	0.05	0.04	4.1
Total consumption	97.99	98.22	101.2	110.6	117.6	125.10	132.4	1.3
Petroleum (million barrels per day)								
Domestic crude production	5.74	5.68	5.76	6.16	5.78	5.36	4.98	0.5
Other domestic production	3.60	3.72	3.77	3.95	3.77	4.19	4.29	1.0
Net imports	10.54	11.24	11.6	12.61	14.44	16.21	18.06	2.1
Consumption	19.71	20.00	20.65	22.54	24.1	25.76	27.30	1.4
Natural gas (trillion ft.^{3})								
Production	19.03	19.13	19.16	20.86	21.39	22.56	22.20	0.6
Net imports	3.50	3.24	3.34	4.73	6.79	7.77	8.60	4.6
Consumption	22.98	21.95	22.29	25.61	28.27	30.42	30.91	1.5

Coal (million short tons)								
Production	1105	1083	1178	1235	1268	1344	1484	1.5
Net imports	−23	−18	−23	−9	3	7	20	N/A
Consumption	1066	1095	1136	1227	1271	1351	1504	1.5
Prices (2003 dollars)								
World oil price (dollars per barrel)	24.10	27.73	43.63	30.99	32.33	33.67	35.00	1.0
Gas Wellhead price (dollars per thousand cubic ft.)	3.06	4.98	5.56	3.63	4.11	4.45	4.83	0.2
Coal Minemouth price (dollars per ton)	18.23	17.93	18.78	17.45	16.99	17.54	18.52	0.1
Average electricity (cents per kilowatthour)	7.4	7.4	7.4	6.6	7.0	7.2	7.3	0.1
Economic indicators								
Real gross domestic product (billion 2000 dollars)	10,075	10,381	11,191	13,063	15,216	17,641	20,293	3.1
GDP Chaintype price index (index, 2000 = 1.000)	1.041	1.060	1.106	1.219	1.371	1.559	1.811	2.5
Real disposable personal income (billion 2000 dollars)	7560	7734	8213	9540	11,152	12,745	14,945	3.0
Value of industrial shipments (billion 1996 dollars)	5067	5105	5464	6167	6872	7669	8506	2.3
Energy intensity (thousand Btu per 2000 dollar of GDP)	9.73	9.47	9.05	8.47	7.74	7.09	6.53	1.7
Carbon dioxide emissions (million metric tons)	5751	5789	5982	6561	6988	7461	7981	1.5

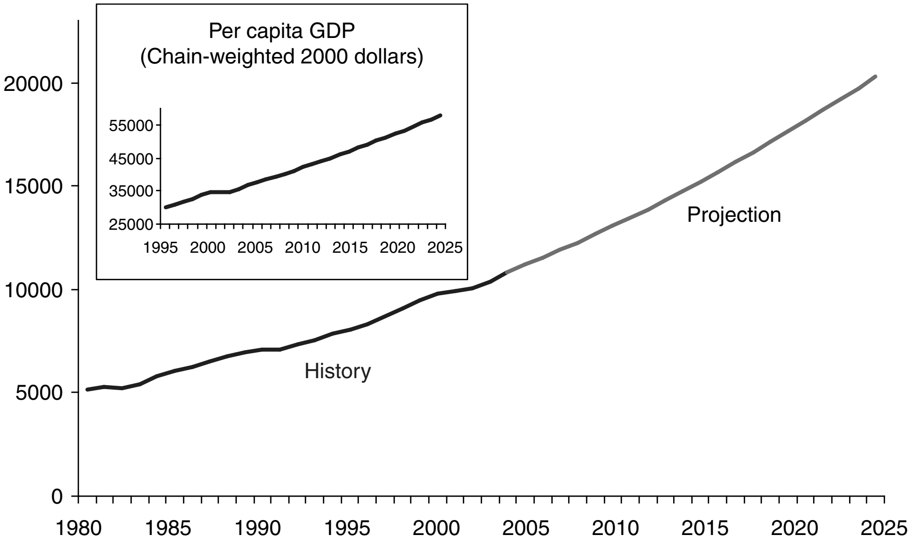

FIGURE 2.1 October oil futures case, U.S. gross domestic product 1982–2025 (billions of chain weighted year 2000 dollars).

From 2003 through 2025, personal disposable income is projected to grow by about 3% per year and disposable income per capita by 2.2% per year. Nonfarm employment is projected to grow by 1.2% per year, and employment in manufacturing is projected to shrink by about 0.6% per year. From 2003 to 2025, industrial output in real value terms is projected to grow by 2.3% per year, compared with 3.2% average annual growth in the services sector.

2.4 Energy Prices

The annual average imported refiners' acquisition cost (IRAC) of crude oil in this projection increases from $27.73 per barrel (2003 dollars) in 2003 to $46.00 per barrel in 2004 and then declines to $31 per barrel in 2010 as new supplies enter the market. It then rises to $35 per barrel in 2025 (Figure 2.2). Note that fuel prices in the graph have all been converted to dollars per million Btu to allow for comparison. In 2025, the average world oil price is expected to be about $62 per barrel in 2025 dollars. The NEMS projection provides the price of a basket of crude oil with types ranging from light 'sweet' (low specific gravity and low sulfur) to heavy 'sour' (high specific gravity and high sulfur). Many readers are accustomed to seeing the price of west Texas intermediate (WTI) crude oil which has typically commanded a premium of from $1.00 to $8.00 dollars per barrel above the IRAC (in 2004 dollars). In 2004 dollars, the average margin between WTI and IRAC for the period 1984 to 2004 is $2.70 per barrel. Like WTI, imported light sweet crude oil has also been sold at a price premium relative to IRAC on the world oil market, with a premium ranging between about $0.50 to $5.00 dollars per barrel above the IRAC price. Because the United States has a large refinery capacity to process heavy sour crude oils, use of the IRAC price rather than the WTI price or the price of imported light sweet crude is more representative of crude oil prices in U.S. energy markets. For countries with refinery capacity that can mostly handle only light sweet crude oils, the reader may assume a price which is about $1 to $5 per barrel higher than the IRAC price assumed for the United States in this projection. The specific value will depend on the extent to which foreign refiners also increase their ability to handle heavy sour crude oils over the forecast horizon.

The projected world oil price forecast is characterized by decreasing prices through 2010 and moderately increasing prices thereafter. This is consistent with a forecast that projects increases in world petroleum demand from about 80 million barrels per day in 2003 to about 116 million barrels per

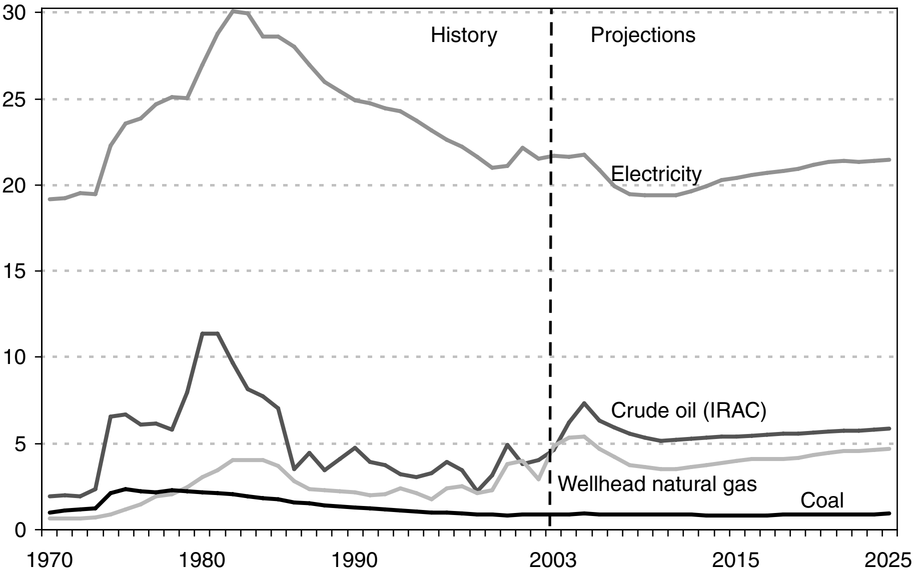

FIGURE 2.2 October oil futures case, energy prices, 1970–2025 (2003 dollars per million Btu).

day in 2025. The projected demand is met by increased oil production both from the OPEC and non-OPEC nations. OPEC oil production is projected to rise to 48.5 million barrels per day in 2025, 57% higher than the 30.6 million barrels per day produced in 2003. The forecast assumes that OPEC will pursue policies intended to increase production, that sufficient resources exist, and that access and capital will be available to expand production. Non-OPEC oil production is expected to increase from 49 to 67.8 million barrels per day between 2003 and 2025.

Average wellhead prices in constant 2003 dollars for natural gas in the United States are projected generally to decrease, from \$5.47 per thousand ft.^{3} (\$5.32 per million Btu) in 2004 to \$3.63 per thousand ft.^{3} (\$3.53 per million Btu) in 2010 as the availability of new natural gas import sources and increased drilling expands available supply. After 2010, wellhead prices are projected to increase gradually, to \$4.83 per thousand ft.^{3} (\$4.70 per million Btu) in 2025 (equivalent to about \$8.50 per thousand ft.^{3} in nominal (current-year) dollars) as demand increases require production from higher-cost domestic unconventional natural gas sources. Growth in LNG imports, Alaska production, and lower-48 production from non-conventional sources are not expected to increase sufficiently to offset the impacts of resource depletion and increased demand.

In the projection, the combination of more moderate increases in coal production, expected improvements in mine productivity, and a continuing shift to low-cost coal from the Powder River Basin in Wyoming leads to a gradual decline in the average minemouth price to approximately \$17.00 per ton (\$0.84 per million Btu) in 2003 dollars in 2015. The price is projected to remain nearly constant between 2015 and 2020, increasing after 2020 as rising natural gas prices and the need for baseload generating capacity lead to the construction of many new coal-fired generating plants. By 2025, the average minemouth price (in 2003 dollars) is projected to be \$18.52 per ton (\$0.92 per million Btu). The projected minemouth coal price in nominal (current-year) terms is expected to be \$31.25 per in 2025.

Average delivered electricity prices in 2003 dollars are projected to decline from 7.4 cents per kWh (\$21.74 per million Btu) in 2003 to a low of 6.6 cents per kWh (\$19.38 per million Btu) in 2010 as a result of an increasingly competitive generation market and a decline in natural gas prices. After 2010, average real electricity prices are projected to increase, reaching 7.3 cents per kWh (\$21.47 per million Btu) in 2025 (equivalent to 12.9 cents per kWh in nominal (current-year) dollars).

2.5 Energy Consumption

Total primary energy consumption in the projection is expected to increase from 98.2 quadrillion Btu in 2003 to 132.4 quadrillion Btu in 2025, an average annual increase of 1.3%, which is less than half the annual rate of growth for projected for GDP.

2.5.1 Residential Energy Consumption

Consistent with population growth rates and household formation, delivered residential energy consumption is projected to grow from 11.6 quadrillion Btu in 2003 to 14.1 quadrillion Btu in 2025 (Figure 2.3), at an average rate of 0.9% per year between 2003 and 2025 (1.0% per year between 2003 and 2010, slowing to 0.8% per year between 2010 and 2025). The most rapid growth in residential energy demand in the projection is expected to be for electricity used to power computers, electronic equipment, and appliances. Natural gas use in the residential sector is projected to grow at an annual rate of 1.1% from 2003 to 2010 and 0.6% from 2010 to 2025.

The projection includes changes in the residential sector that have offsetting influences on the forecast of energy consumption, including more rapid growth in the total number of U.S. households, higher delivered prices for natural gas, electricity, and distillate fuel, and a better accounting of additions to existing homes and the height of ceilings in new homes.

2.5.2 Commercial Energy Consumption

The forecast for commercial energy consumption is largely driven by an expected annual rate of growth in commercial floor space that is projected to average 1.7% per year between 2003 and 2025. Consistent with the projected increase in commercial floor space, delivered commercial energy consumption is projected to grow at an average annual rate of 1.9% between 2003 and 2025, reaching 12.4 quadrillion Btu in 2025. The most rapid increase in commercial energy demand is projected for electricity used for computers, office equipment, telecommunications, and miscellaneous small appliances.

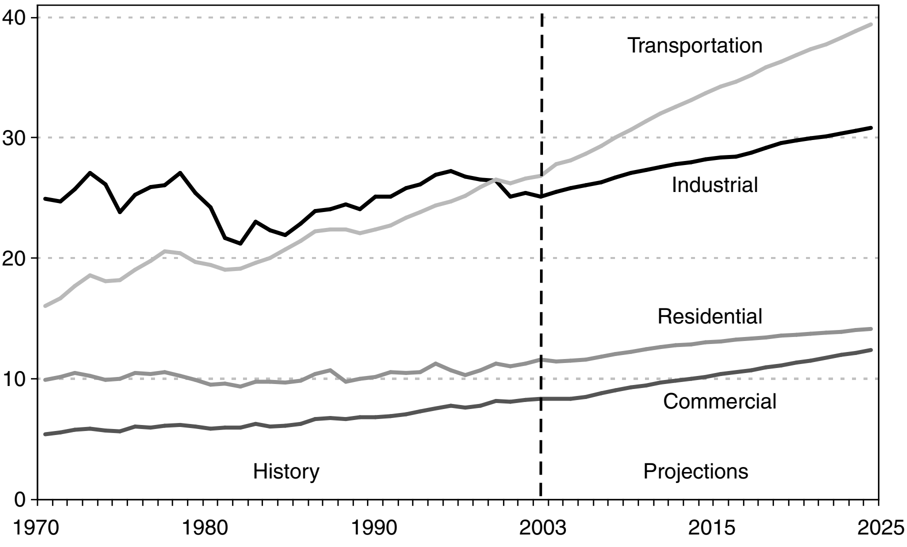

FIGURE 2.3 October oil futures case, delivered energy consumption by sector, 1970–2025 (quadrillion Btu).

2.5.3 Industrial Energy Consumption

Industrial energy consumption in the October oil futures case is projected to increase at an average rate of 0.9% per year between 2003 and 2025, reaching 30.8 quadrillion Btu in 2025. Key to the slower growth rate of industrial energy consumption as compared to the annual U.S. energy consumption rate of 1.3% is a continued shift of the U.S. economy toward services and away from energy-intensive industries. The value of shipments, a measure of industrial economic activity, is projected to increase at an annual rate of 2.3% as compared to the annual growth in the economy as a whole of 3.1%.

2.5.4 Transportation Energy Consumption

Energy consumption in the transportation sector is projected to grow at an average annual rate of 1.7% between 2003 and 2025 in the projection, reaching 39.4 quadrillion Btu in 2025. The growth in transportation energy demand is largely driven by the increasing personal disposable income, projected to grow annually at about 3%, consumer preferences for driving larger cars with more horsepower, and an increase in the share of light trucks and sports utility vehicles that make up light-duty vehicles. Total vehicle miles traveled by light-duty vehicles is projected to increase at an annual rate of 2% between 2003 and 2025 because of the increase in personal disposable income and other demographic factors.

2.5.5 Electricity Sector

Total electricity consumption, including both purchases from electric power producers and on-site generation, is projected to grow from 3657 billion kWh in 2003 to 5470 billion kWh in 2025, increasing at an average rate of about 1.8% per year. Rapid growth in electricity use for computers, office equipment, and a variety of electrical appliances in the end use sectors is partially offset in the forecast by improved efficiency in these and other, more traditional electrical applications and by slower growth in electricity demand in the industrial sector.

2.5.6 Demand for Natural Gas

Total demand for natural gas is projected to increase at an average annual rate of 1.5% from 2003 to 2025 (Figure 2.4), primarily as a result of increasing use for electricity generation and industrial applications that together account for about 75% of the projected growth in natural gas demand from 2003 to 2025. Total projected consumption of natural gas in 2025 is 30.9 trillion ft.^3, or 31.8 quadrillion Btu. The growth in demand for natural gas slows in the later years of the forecast (0.9% per year from 2015 to 2025, compared with 2.2% per year from 2003 to 2010), as rising natural gas prices lead to the construction of more coal-fired capacity for electricity generation.

2.5.7 Demand for Coal

Total coal consumption is projected to increase from 1095 million short tons (about 22.7 quadrillion Btu) in 2003 to 1505 million short tons (30.5 quadrillion Btu) in 2025, an annual growth rate of 1.5% per year. The increase in coal consumption results almost entirely from increased coal demand for electricity generation because of the expected price increases of natural gas. Total coal consumption for electricity generation is projected to increase by an average of 1.6% per year, from 1004 million short tons (20.5 quadrillion Btu) in 2003 to 1421 million short tons (28.6 quadrillion Btu) in 2025.

2.5.8 Demand for Petroleum

Total petroleum demand is projected to grow at an average annual rate of 1.4% in the projection, from 20.0 million barrels per day (39.1 quadrillion Btu) in 2003 to 27.3 million barrels per day

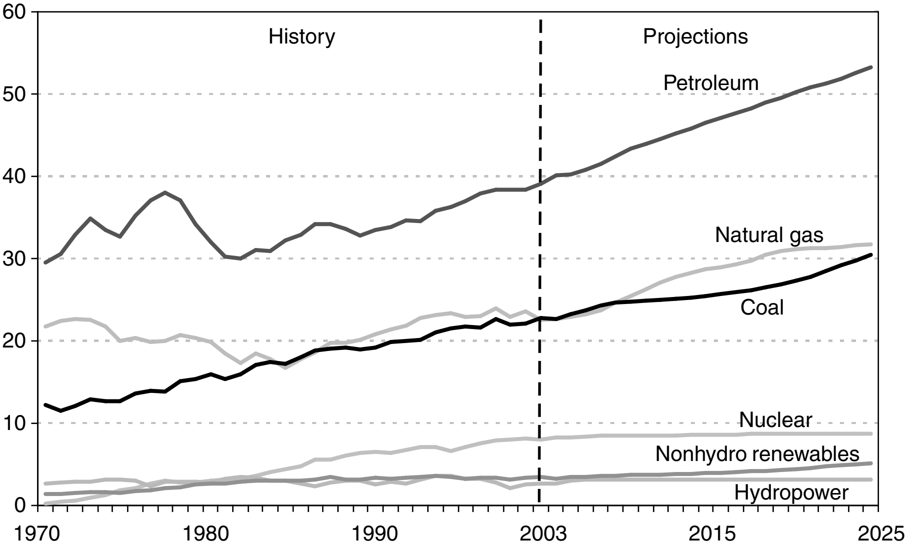

FIGURE 2.4 October oil futures case, energy consumption by fuel, 1970–2025 (quadrillion Btu).

(53.2 quadrillion Btu) in 2025. Almost all of the growth is attributable to the growth in transportation sector demand for petroleum products.

Total marketed renewable fuel consumption (including ethanol for gasoline blending, of which 0.2 quadrillion Btu is included with "petroleum products" consumption in Table 2.1), is projected to grow by 1.6% per year in the projection, from 6.1 quadrillion Btu in 2003 to 8.8 quadrillion Btu in 2025, as a result of state mandates for renewable electricity generation, higher natural gas prices, and the effect of production tax credits. About 60% of the projected demand for renewables in 2025 is for grid-related electricity generation (including combined heat and power), and the rest is for dispersed heating and cooling, industrial uses, and fuel blending. Renewable generating technologies are usually not as competitive in the projection as natural-gas-fired or advanced coal-fired technologies, because the costs for natural gas and advanced coal-fired technologies are usually lower, on a kWh basis, than those for renewable generation.

2.6 Energy Intensity

Energy intensity, as measured by energy use per 2000 dollar of GDP, is projected to decline at an average annual rate of 1.6% in the projection, with efficiency gains and structural shifts in the economy offsetting growth in demand for energy services (Figure 2.5). The projected rate of decline in the October oil futures case falls between the historical averages of 2.3% per year from 1970 to 1986, when energy prices increased in real terms, and 0.7% per year from 1986 to 1992, when energy prices were generally falling.

Since 1992, energy intensity has declined on average by 1.9% per year. During this period, the role of energy-intensive industries in the U.S. economy has fallen sharply. The share of industrial output from the energy-intensive industries declined on average by 1.3% per year from 1992 to 2003. In the projection, the energy-intensive industries' share of total industrial output is projected to continue declining but at a slower rate of 0.8% per year, which leads to the projected slower annual rate of reduction in energy intensity.

Historically, energy use per person has varied over time with the level of economic growth, weather conditions, and energy prices, among many other factors. During the late 1970s and early 1980s, energy

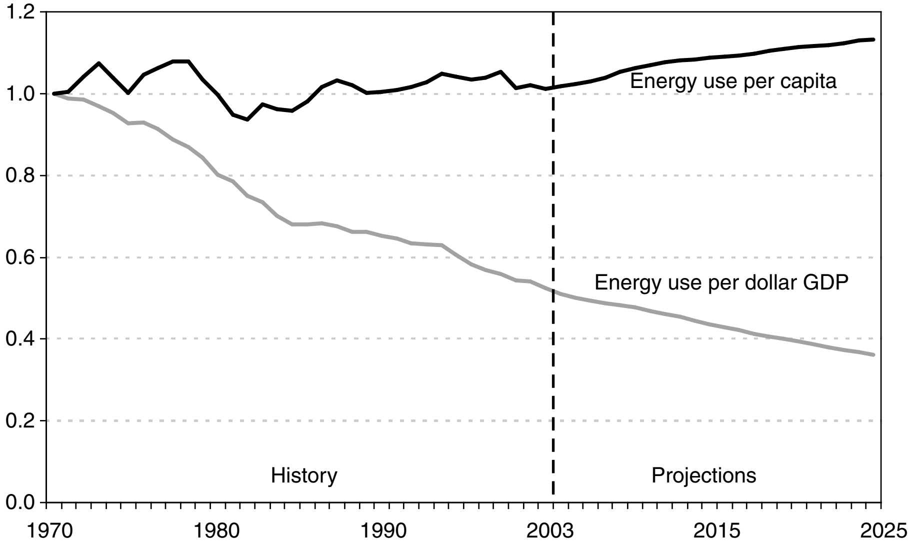

FIGURE 2.5 October oil futures case, energy use per capita and per dollar of gross domestic product, 1970–2025 (index, 1970 = 1).

consumption per capita fell in response to high energy prices and weak economic growth. Starting in the late 1980s and lasting through the mid-1990s, energy consumption per capita increased with declining energy prices and strong economic growth. Per capita energy use is expected to increase in this projection, with growth in demand for energy services only partially offset by efficiency gains. Per capita energy use increases by an average of almost 0.5% per year between 2003 and 2025 in the projection.

The potential for more energy conservation has received increased attention recently as energy prices have risen. Although energy conservation is projected to be induced through energy price increases, the projection does not assume policy-induced conservation measures beyond those in existing legislation and regulation, nor does it assume behavioral changes beyond those experienced in the past.

2.7 Electricity Generation

The natural gas share of electricity generation (including generation in the end use sectors) is projected to increase from 16% in 2003 to 24% in 2025. The share from coal is projected to decrease from 51% in 2003 to 50% in 2025. The projection estimates that 89 GW of new coal-fired generating capacity will be constructed between 2004 and 2025.

In the electric power sector, natural gas consumption increases from 5.0 trillion ft.^3 in 2003 to 9.4 trillion ft.^3 in 2025, accounting for about 31% of total demand for natural gas in 2025 as compared with 23% in 2003. The increase in natural gas consumption for electricity generation results from both the construction of new gas-fired generating plants and higher capacity utilization at existing plants. Most new electricity generation capacity is expected to be fueled by natural gas, because natural-gas-fired generators are projected to have advantages over coal-fired generators that include lower capital costs, higher fuel efficiency, shorter construction lead times, and lower emissions. Toward the end of the forecast, however, when natural gas prices rise substantially, coal-fired power plants are expected to be competitive for new capacity additions.

Nuclear generating capacity in the October oil futures case is projected to increase from 99.2 GW in 2003 to 102.7 GW in 2025 as a result of upgrades of existing plants between 2003 and 2025. All existing

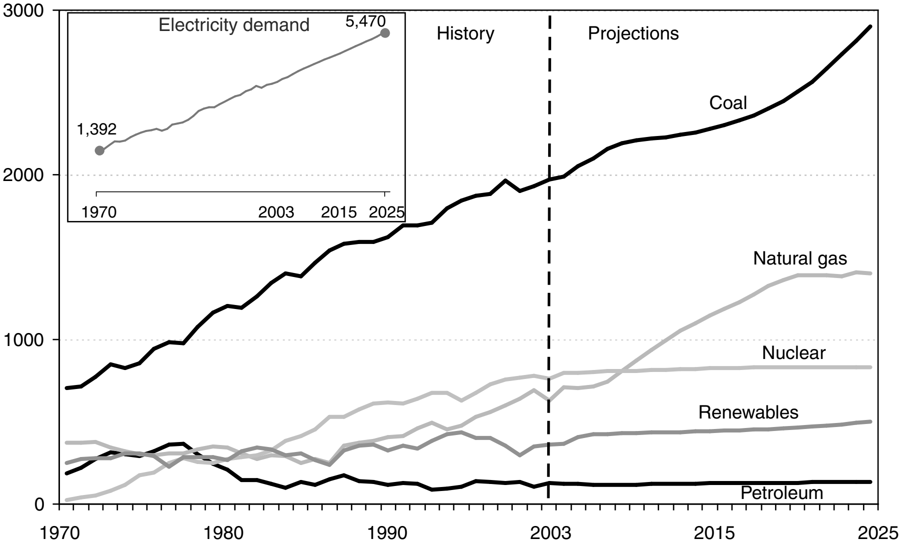

FIGURE 2.6 October oil futures case, electricity generation by fuel, 1970–2025 (billion kilowatthours).

nuclear plants are projected to continue to operate, but new plants are not expected to be economical. Total nuclear generation is projected to grow from 764 billion kWh in 2003 to 830 billion kWh in 2025 in the projection (Figure 2.6).

The use of renewable technologies for electricity generation is projected to grow slowly, both because of the relatively low costs of fossil-fired (primarily natural gas and coal) generation and because competitive electricity markets favor less capital-intensive technologies. Where enacted, state renewable portfolio standards, which specify a minimum share of generation or sales from renewable sources, are included in the forecast. The projection also includes the extension of the production tax credit for wind and biomass through December 31, 2005, as enacted in H.R. 1308, the Working Families Tax Relief Act of 2004. Current Congressional energy bills pending before Congress, including H.R. 6 (or the Senate energy bill) have not been included in this projection because they had not been enacted at the time this projection was developed.

Total renewable generation, including combined heat and power generation, is projected to grow from 359 billion kWh in 2003 to 497 billion kWh in 2025, increasing by 1.5% per year.

2.8 Energy Production and Imports

Total energy consumption is expected to increase more rapidly than domestic energy supply through 2025. As a result, net imports of energy are projected to meet a growing share of energy demand (Figure 2.7). Net imports are expected to constitute 38% of total U.S. energy consumption in 2025, up from 27% in 2003.

2.8.1 Petroleum Supply and Imports

Projected U.S. crude oil production is projected to increases from 5.7 million barrels per day in 2003 to a peak of 6.3 million barrels per day in 2009 as a result of expected higher prices than the 1990s, increased production offshore, predominantly from the deep waters of the Gulf of Mexico. Beginning in 2010, U.S.

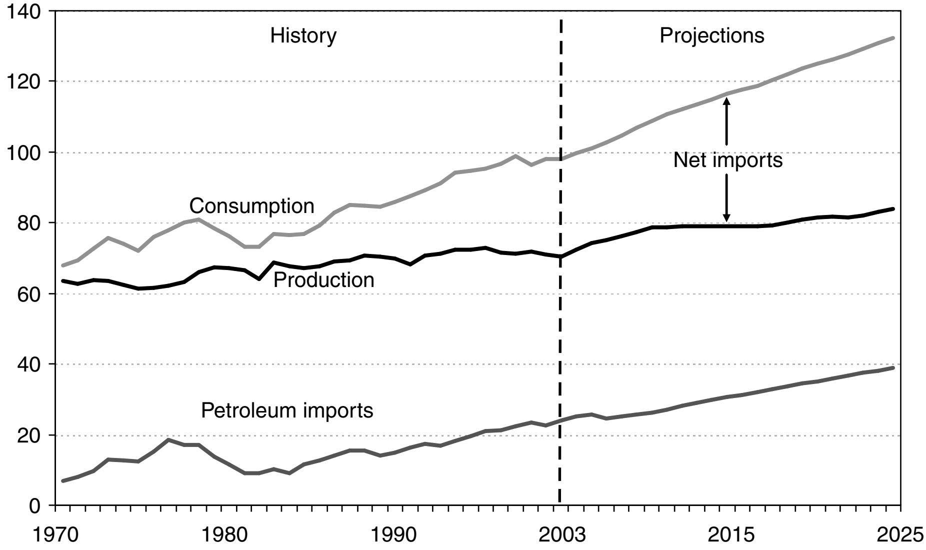

FIGURE 2.7 October oil futures case, total energy production and consumption, 1970–2025 (quadrillion Btu).

crude oil production begins to decline, falling to 5.0 million barrels per day in 2025 (Table 2.1) as depletion effects dominate technological advances and gradual price increases.

Total domestic petroleum supply (crude oil, natural gas plant liquids, refinery processing gains, and other refinery inputs) follows the same pattern as crude oil production in the forecast, increasing from 9.1 million barrels per day in 2003 to a peak of 10.0 million barrels per day in 2009, then declining to 9.3 million barrels per day in 2025.

In 2025, net petroleum imports, including both crude oil and refined products, are expected to account for 66% of demand (on the basis of barrels per day), up from 56% in 2003. Net imports of refined petroleum products account for between 12% and 14% of total net imports for the forecast horizon.

2.8.2 Natural Gas Supply and Imports

Growth in U.S. natural gas supplies will depend on unconventional domestic production, Canadian imports, natural gas from Alaska, and imports of LNG. Domestic natural gas production is projected to increase from 19.1 trillion ft.^{3} in 2003 to 22.2 quadrillion Btu in 2025 in the projection (Table 2.1). Lower-48 onshore natural gas production is projected to increase from 13.9 trillion ft.^{3} in 2003 to a peak of 15.7 trillion ft.^{3} in 2012 before falling to 14.7 trillion ft.^{3} in 2025. Lower-48 offshore production, which was 4.7 trillion ft.^{3} in 2003, is projected to increase in the near term (to 5.6 trillion ft.^{3} by 2015) because of the expected development of some large deepwater fields, including Mad Dog, Entrada, and Thunder Horse. After 2015, offshore production is projected to decline to 5.3 trillion ft.^{3} in 2025.

Unconventional production is expected to become the largest source of U.S. natural gas supply. As a result of technological improvements and rising natural gas prices, natural gas production from relatively abundant unconventional sources (tight sands, shale, and coalbed methane) is projected to increase more rapidly than conventional production. Lower-48 unconventional gas production grows from 6.6 trillion ft.^{3} in 2003 to 8.6 trillion ft.^{3} in 2025 and from 35% of total lower-48 production in 2003 to 43% in 2025.

Production of lower-48 non-associated (NA) conventional natural gas declines from 9.5 trillion ft^3 in 2003 to 8.9 trillion ft.^{3} in 2025, as resource depletion causes exploration and development costs to increase. Offshore NA natural gas production is projected to rise slowly to a peak of 3.9 trillion ft.^{3} in 2008, then decline to 3.8 trillion ft.^{3} in 2025.

Production of associated-dissolved (AD) natural gas from lower-48 crude oil reserves is projected to increase from 2.5 trillion ft.^{3} in 2003 to 3.2 trillion ft.^{3} in 2010 due to a projected increase in offshore AD gas production. After 2010, both onshore and offshore AD gas production are projected to decline, and total lower-48 AD gas production falls to 2.5 trillion ft.^{3} in 2025.

Decreases in natural gas imports from Canada are expected to be offset by substantial increases in LNG imports and the development of the North Slope Alaska natural gas pipeline. Canadian imports are projected to decline from 2003 levels of 3.1 trillion ft.^{3} to about 2.5 trillion ft.^{3} in 2010, followed by an increase after 2010 to 3.1 trillion ft.^{3} in 2016 as a result of rising natural gas prices, the introduction of gas from the Mackenzie Delta, and increased production of coalbed methane. After 2016, because of reserve depletion effects and growing domestic demand in Canada, net U.S. imports of Canadian natural gas are projected to decline to 2.7 trillion ft.^{3} in 2025. That is, pipeline imports from Canada decline at the end of the forecast, because Canada's gas consumption increases more rapidly than its production. The forecasted supply of natural gas from Canada reflects revised Energy Information Administration (EIA) expectations about Canadian natural gas production, particularly coalbed methane and conventional production in Alberta, based in part on data and projections from Canada's National Energy Board and other sources.

With the exception of the facility at Everett, Massachusetts, three of the four existing U.S. LNG terminals (Cove Point, Maryland; Elba Island, Georgia; and Lake Charles, Louisiana) are expected to expand by 2007; and additional facilities are expected to be built in New England and elsewhere in the lower-48 States, serving the Gulf, mid-Atlantic, and south Atlantic states, including a new facility in the Bahamas serving Florida via a pipeline. Another facility is projected to be built in Baja California, Mexico, serving a portion of the California market. Total net LNG imports to the United States and the Bahamas are projected to increase from 0.4 trillion ft.^{3} in 2003 to 6.2 trillion ft.^{3} in 2025.

The North Slope Alaska natural gas pipeline is projected to begin transporting Alaskan natural gas to the lower-48 states in 2017 as a result of favorable investment economics and increasing natural gas prices. In 2025, total Alaskan natural gas production is projected to be 2.2 trillion ft.^{3} in the October oil futures case, compared with 0.4 trillion ft.^{3} in 2003.

2.8.3 Coal Supply

As domestic coal demand grows in the forecast, U.S. coal production is projected to increase at an average rate of 1.4% per year, from 1083 million short tons in 2003 to 1484 million short tons in 2025. Production from mines west of the Mississippi River is expected to provide the largest share of the incremental coal production. In 2025, nearly two-thirds of coal production is projected to originate from the western states.

2.9 Carbon Dioxide Emissions

Carbon dioxide emissions from energy use are projected to increase from 5789 million metric tons in 2003 to 7981 million metric tons in 2025, an average annual increase of 1.5% (Figure 2.8). The carbon dioxide emissions intensity of the U.S. economy is projected to fall from 558 metric tons per million dollars of GDP in 2003 to 393 metric tons per million dollars in 2025—an average decline of 1.6% per year.

By sector, including the emissions associated with the electricity consumed, carbon dioxide emissions for 2003 to 2025 are projected to grow at 1.1% per year in the residential sector, 2.1% per year for the commercial sector, 1.0% per year for the industrial sector, and 1.7% per year for transportation. Power sector carbon dioxide emissions are expected to grow at 1.7% per year but these are already included in the sectoral emissions listed above.

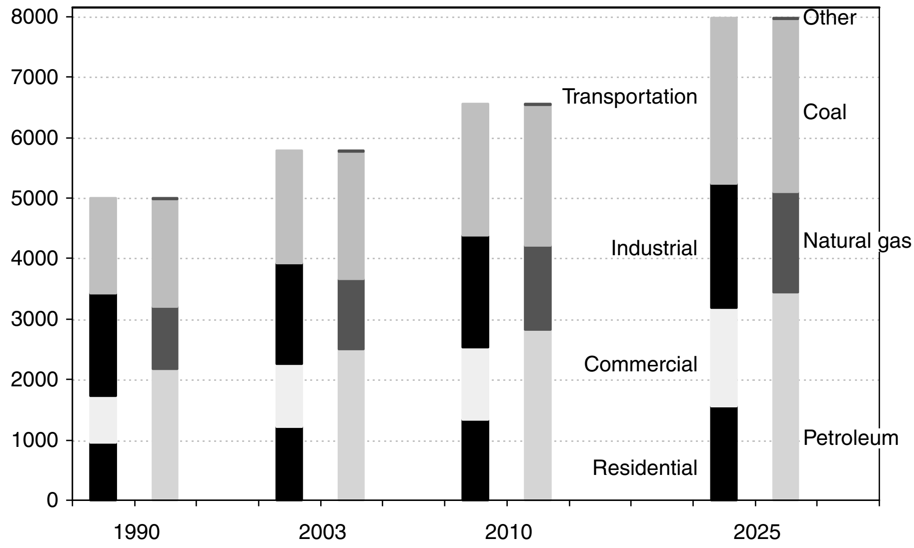

FIGURE 2.8 October oil futures case, U.S. carbon dioxide emissions by sector and fuel, 1990–2025 (million metric tons)-in progress.

2.10 Summary of the AEO2006 Reference Case Projection

2.10.1 Major Changes Reflected in the AEO2006 Reference Case

AEO2006 is the first edition of the *Annual Energy Outlook* (*AEO*) to provide projections through 2030. The *AEO2006* reference case projection incorporates new regulatory changes and laws that were issued after the release of *AEO2005* and before completion of *AEO2006*. Major regulatory changes that affect air emissions from electricity power plants include two rules by the Environmental Protection Agency (EPA) that were not represented in the October oil futures case: the Clean Air Interstate Rule (CAIR), issued on March 10, 2005 and the Clean Air Mercury Rule (CAMR), issued on March 15, 2005.* The new rules are expected to significantly reduce sulfur dioxide, nitrogen oxides, and mercury emissions from electric power plants over the next two decades.

The Energy Policy Act of 2005 (*EPACT2005*, Public Law 109–58), a statute that was signed into to law on August 8, 2005, is also new for *AEO2006*. The act provides tax incentives and loan guarantees for energy production of various types including new nuclear generation (up to 6 GW), integrated gasification combined cycle (IGCC) coal power generation, renewable generation, ethanol use for transportation, and a variety of efficiency programs intended to reduce energy consumption, primarily in the residential and commercial sectors. The *AEO2006* reference case only includes those sections of the *EPACT2005* that establish specific tax credits, incentives, or standards, comprising about 30 of the roughly 500 sections in the legislation.

The world crude oil prices in the *AEO2006* reference case are also significantly higher than those in the October oil futures case. The world crude oil price is now expressed in terms of the average price of imported *low-sulfur* crude oil to U.S. refiners to provide a crude oil price that is more consistent with those reported in the media. Light crude oil import prices are projected to increase from $40.49 per barrel (2004 dollars) in 2004 to $54.08 per barrel in 2025 and to $56.97 per barrel in 2030.

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*see http://www.epa.gov/CAIR/ and http://www.epa.gov/oar/mercuryrule/

The higher prices for imported light, low-sulfur crude oil result from major changes in expectations for key drivers of the crude oil market. First, major oil companies lack access to resources in some key oil-rich countries and that situation is not expected to change over the projection period. Second, in attractive oil resource regions where foreign investment may be welcome, political instability and economic risk limit foreign investments. Third, revenues from national oil companies in key oil-rich countries flow to governments which are facing increasing demands placed on them for social, welfare, and physical infrastructure projects to service rapidly growing restive populations. In some cases, such demands have resulted in unilateral changes to agreements that have increased government revenues and increased investment risks to potential investors. Unilateral changes to agreements to contracts are likely to reduce the rate of new investments to develop oil reserves. Finally, since the world economies have continued to grow robustly over the past 2–3 years in spite of crude oil prices that have exceeded $40 per barrel, and petroleum demand has seen only small changes, there appears to be little motivation for key OPEC suppliers to aggressively expand production, substantially lower crude oil prices, and reduce their revenues.

Most of the trends and the reasons for the trends in the October oil futures case are similar to the trends in the *AEO2006* reference case. Consequently, only the major differences in the trends and their explanations will be highlighted in this section.

None of the projections or scenarios provided in *AEO2005* or *AEO2006* reflect the onset of "peak oil." Historically, crude oil prices have shown significant variations with prices in constant 2004 dollars; for example, crude oil prices exceeded $100 per barrel in the late 1970s and early 1980s. The new high world oil price path in *AEO2006* reflects a new investment and access constrained outlook for crude oil in which the world economies appear able to assimilate the new world oil price regime and crude oil exporters are happy to reap the revenues.

The challenge to oil-rich producers is balance the desire to increase prices and revenues with the potential to cause worldwide economic damage stimulate technological breakthroughs that could undermine their revenues in the longer term. Although specific innovations and technological successes cannot be anticipated or guaranteed, innovation and technological and process advances have historically preceded historical price declines from lofty highs (e.g., horizontal drilling, 3-D and 4-D simulations, the breakthroughs for inexpensive computing, and many others). Breakthroughs that allow relatively inexpensive exploitation of oil shale, for example, could be one such future breakthrough for crude oil production if prices remain too high; breakthroughs in coal-to-liquids technologies, and exploitation of ultraheavy crude oils might be others. For this reason, it is appropriate for investors and planners to consider a plausible range of world oil price scenarios as provided in this chapter or in the *AEO2006* alternative oil price scenarios.

The challenge and potentially serious pitfall for forecasters and investors is to avoid extrapolating short-term trends into long-term projections without supporting analysis that focuses on the changing fundamentals of the industry.

2.10.2 Implications of Higher World Oil Prices

The higher world oil prices in the *AEO2006* reference case have important implications for the projected evolution of energy markets. The most significant impact is in the outlook for petroleum imports. Net imports of petroleum are projected to meet a growing share of total petroleum demand. However, the higher world oil prices in the *AEO2006* reference case lead to greater domestic crude oil production and lower demand, which reduces the need for petroleum imports to 60% in 2025 and 62% of petroleum demand (on the basis of barrels per day) in 2030, up from 58% in 2004. Table 2.2 provides a tabular summary of the *AEO2006* reference case.

The higher world oil prices also impact fuel choice and vehicle efficiency decisions in the transportation sector. Higher oil prices increase the demand for unconventional sources of transportation fuel, such as ethanol and biodiesel, and stimulate coal-to-liquids (CTL) production for the first time. The move to alternative liquids production is highly sensitive to the level of oil prices.

TABLE 2.2 Total Energy Supply and Disposition in the *AEO2006* Reference Case: Summary, 2003–2030

Energy and Economic Factors	2003	2004	2010	2015	2020	2025	2030	2004–2030(%)
Primary energy production (quadrillion Btu)								
Petroleum	14.40	13.93	14.83	14.94	14.41	13.17	12.25	−0.5
Dry natural gas	19.63	19.02	19.13	20.97	22.09	21.80	21.45	0.5
Coal	22.12	22.86	25.78	25.73	27.30	30.61	34.10	1.6
Nuclear power	7.96	8.23	8.44	8.66	9.09	9.09	9.09	0.4
Renewable energy	5.69	5.74	7.08	7.43	8.00	8.61	9.02	1.8
Other	0.72	0.64	2.16	2.85	3.16	3.32	3.44	6.7
Total	70.52	70.42	77.42	80.58	84.05	86.59	89.36	0.9
Net imports (quadrillion Btu)								
Petroleum	24.19	25.88	26.22	28.02	30.39	33.11	36.49	1.3
Natural gas	3.39	3.49	4.45	5.23	5.15	5.50	5.72	1.9
Coal/other (−indicates export)	−0.45	−0.42	−0.58	0.20	0.90	1.54	2.02	NA
Total	27.13	28.95	30.09	33.44	36.44	40.15	44.23	1.6
Consumption (quadrillion Btu)								
Petroleum products	38.96	40.08	43.14	45.69	48.14	50.57	53.58	1.1
Natural gas	23.04	23.07	24.04	26.67	27.70	27.78	27.66	0.7
Coal	22.38	22.53	25.09	25.66	27.65	30.89	34.49	1.7
Nuclear power	7.96	8.23	8.44	8.66	9.09	9.09	9.09	0.4
Renewable energy	5.70	5.74	7.08	7.43	8.00	8.61	9.02	1.8
Other	0.02	0.04	0.07	0.08	0.05	0.05	0.05	0.9
Total	98.05	99.68	107.87	114.18	120.63	126.99	133.88	1.1
Petroleum (million barrels per day)								
Domestic crude production	5.69	5.42	5.88	5.84	5.55	4.99	4.57	−0.7
Other domestic production	3.10	3.21	3.99	4.50	4.90	5.45	5.84	2.3
Net imports	11.25	12.11	12.33	13.23	14.42	15.68	17.24	1.4
Consumption	20.05	20.76	22.17	23.53	24.81	26.05	27.57	1.1
Natural gas (trillion ft.^{3})								
Production	19.11	18.52	18.65	20.44	21.52	21.24	20.90	0.5
Net imports	3.29	3.40	4.35	5.10	5.02	5.37	5.57	1.9
Consumption	22.34	22.41	23.35	25.91	26.92	26.99	26.86	0.7

(continued)

TABLE 2.2 (***Continued***)

Energy and Economic Factors	2003	2004	2010	2015	2020	2025	2030	2004–2030(%)
Coal (million short tons)								
Production	1083	1125	1261	1272	1355	1530	1703	1.6
Net imports	−18	−21	−26	5	36	63	83	NA
Consumption	1095	1104	1233	1276	1390	1592	1784	1.9
Prices (2004 dollars)								
Imported low-sulfur light crude oil (dollars per barrel)	31.72	40.49	47.29	47.79	50.70	54.08	56.97	1.3
Imported crude oil (dollars per barrel)	28.46	35.99	43.99	43.00	44.99	47.99	49.99	1.3
Domestic natural gas at wellhead (dollars per thousand cubic ft.)	5.08	5.49	5.03	4.52	4.90	5.43	5.92	0.3
Domestic coal at minemouth (dollars per short ton)	18.40	20.07	22.23	20.39	20.20	20.63	21.73	0.3
Average electricity price (cents per kilowatthour)	7.6	7.6	7.3	7.1	7.2	7.4	7.5	0.0
Economic indicators								
Real gross domestic product (billion 2000 dollars)	10,321	10,756	13,043	15,082	17,541	20,123	23,112	3.0
GDP chain-type price index (index, 2000=1.000)	1.063	1.091	1.235	1.398	1.597	1.818	2.048	2.5
Real disposable personal income (billion 2000 dollars)	7742	8004	9622	11,058	13,057	15,182	17,562	3.1
Value of manufacturing shipments (billion 2000 dollars)	5378	5643	6355	7036	7778	8589	9578	2.1
Energy intensity (thousand Btu per 2000 dollar of GDP)	9.51	9.27	8.28	7.58	6.88	6.32	5.80	−1.8
Carbon dioxide emissions (million metric tons)	5815	5919	6365	6718	7119	7587	8115	1.2

Quantities are derived from historical volumes and assumed thermal conversion factors. Other production includes liquid hydrogen, methanol, supplemental natural gas, and some inputs to refineries. Net imports of petroleum include crude oil, petroleum products, unfinished oils, alcohols, ethers, and blending components. Other net imports include coal coke and electricity. Some refinery inputs appear as petroleum consumption. Other consumption includes net electricity imports, liquid hydrogen, and methanol.

Source: From *AEO2006* National Energy Modeling System, run AEO2006.D111905A.

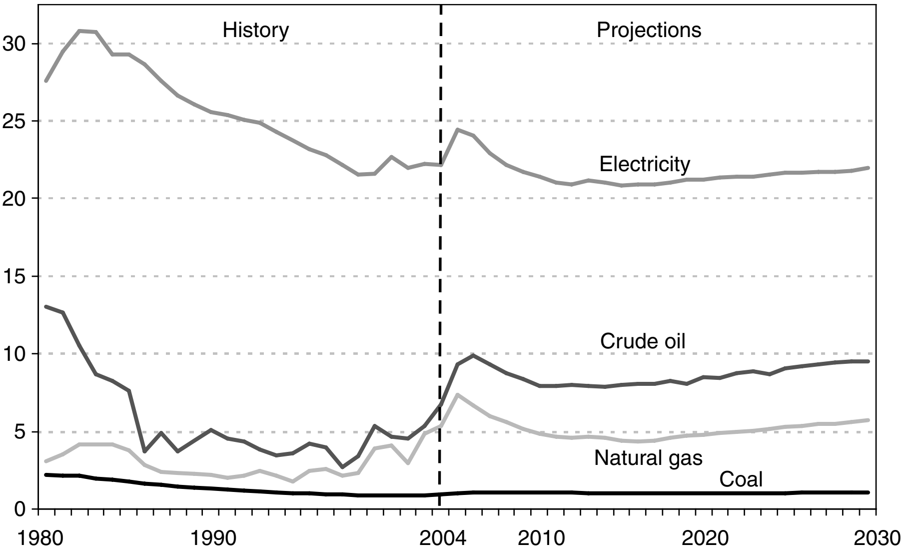

FIGURE 2.9 *AEO2006* reference case, energy prices, 1980–2030 (2004 dollars per million Btu).

2.10.2.1 Economic Growth

Key interest rates, the federal funds rate, the nominal yield on the 10-year treasury note, and the AA utility bond rate are slightly lower compared to the October oil futures case. Also, the projected value of industrial shipments has been revised downward, in part in response to the higher projected energy prices in the *AEO2006* reference case. Despite the higher energy prices in the *AEO2006* reference case relative to the October oil futures case, GDP is projected to grow at an average annual rate of 3.0% from 2004 to 2030 in *AEO2006*, identical to the 3.0% per year growth from 2004 through 2025 projected in the October oil futures case.

2.10.2.2 Energy Prices

In the *AEO2006* reference case, the average world crude oil price increases from $40.49 per barrel (2004 dollars) in 2004 to $59.10 per barrel in 2006 and then declines to $46.90 per barrel in 2014 as new supplies enter the market. It then rises slowly to $54.08 per barrel in 2025 (Figure 2.9).

Average U.S. wellhead natural gas prices are projected to gradually decline from their present level as increased drilling brings on new supplies and new import sources become available, falling to $4.46 per thousand ft.^{3} (2004 dollars) in 2016. After 2016, wellhead prices are projected to increase gradually, to over $5.40 per thousand ft.^{3} in 2025 and over $5.90 per thousand ft.^{3} in 2030. The projected wellhead natural gas prices in the *AEO2006* reference case from 2016 to 2025 are consistently higher than the Octobers oil futures case, ranging roughly from 25 to 60 cents per thousand ft.^{3} higher, primarily due to higher exploration and development costs.

Average delivered electricity prices are projected to decline from 7.6 cents per kWh (2004 dollars) in 2004 to a low of 7.1 cents per kWh in 2018 as a result of falling natural gas prices and, to a lesser extent, coal prices. After 2018, average real electricity prices are projected to increase, reaching 7.4 cents per kWh in 2025 and 7.5 cents per kWh in 2030.

2.10.2.3 Energy Consumption

Total primary energy consumption in the *AEO2006* reference case is projected to increase from 99.7 quadrillion Btu in 2004 to 127.0 quadrillion Btu in 2025 (an average annual increase of 1.2%), 5.4 quadrillion Btu less than in October futures case. In 2025, coal, nuclear, and renewable energy consumption are higher, while petroleum and natural gas consumption are lower in the *AEO2006*

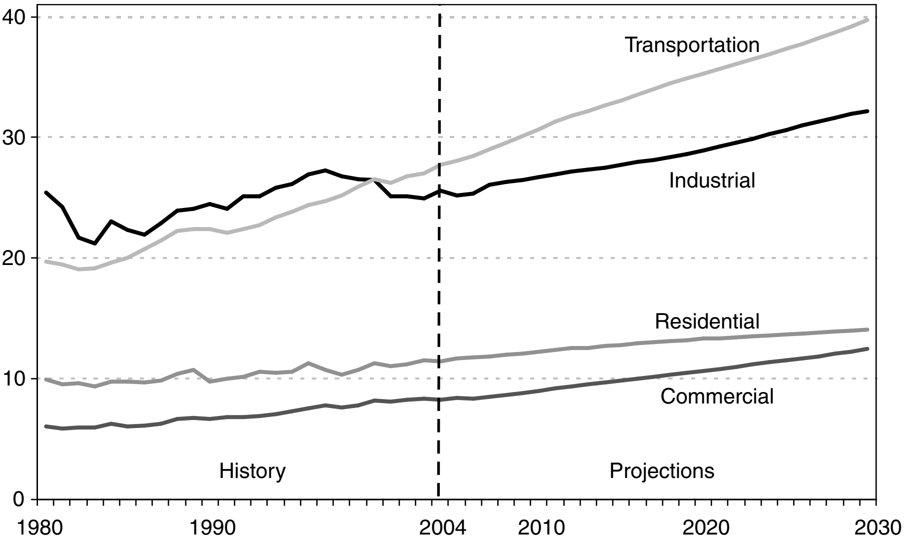

FIGURE 2.10 *AEO2006* reference case, delivered energy consumption by sector, 1980–2030 (quadrillion Btu).

reference case. Among the most important factors accounting for the differences are higher energy prices, particularly petroleum and natural gas prices; lower projected growth rates in the manufacturing portion of the industrial sector, which traditionally includes the most energy-intensive industries; greater penetration by hybrids and diesel vehicles in the transportation sector as consumers focus more on efficiency; and the impact of the recently passed *EPACT2005*, which reduces energy consumption in the residential and commercial sectors and lowers projected growth in electricity demand.

Total petroleum consumption is projected to grow in the *AEO2006* reference case, from 20.8 million barrels per day in 2004 to 26.1 million barrels per day in 2025, 1.2 million barrels per day lower in 2025 than in the October futures case. Petroleum demand growth in the *AEO2006* reference case is lower in all sectors due largely to the impact of the much higher oil prices in *AEO2006*, with almost two-thirds of the decline taking place in the transportation sector.

Total consumption of natural gas in the *AEO2006* reference case is projected to increase from 22.4 tcf in 2004 to 27.0 tcf by 2025 (Figure 2.10), 3.9 tcf lower then projected in the October oil futures case, due mostly to the impact of higher natural gas prices. After peaking at 27.0 tcf, natural gas consumption is projected to fall slightly by 2030 as natural gas loses market share to coal for electricity generation in the later years of the projection due to the higher natural gas prices.

In the *AEO2006* reference case, total coal consumption is projected to increase from 1104 million short tons in 2004 to 1592 million short tons in 2025—84 million short tons more than the 1508 million tons in the October oil futures case. Coal consumption is projected to grow at a faster rate in *AEO2006* toward the end of the projection, particularly after 2020, as coal captures market share from natural gas in power generation due to increasing natural gas prices and as coal use for CTL production grows. Coal was not projected to be used for CTL production in the October oil futures case. In the *AEO2006* reference case, total coal consumption for electricity generation is projected to increase from 1235 million short tons in 2020 to 1502 million short tons by 2030, an average rate of 2.0% per year, and coal use for CTL production increases from 62 million short tons in 2020 to 190 million short tons in 2030.

2.10.2.4 Electricity Generation

In the *AEO2006* reference case, the projected average prices of natural gas and coal delivered to electricity generators in 2025 are higher than the comparable prices in the October oil futures case. While coal consumption in 2025 is similar in both projections, the increase in natural gas prices together with slower

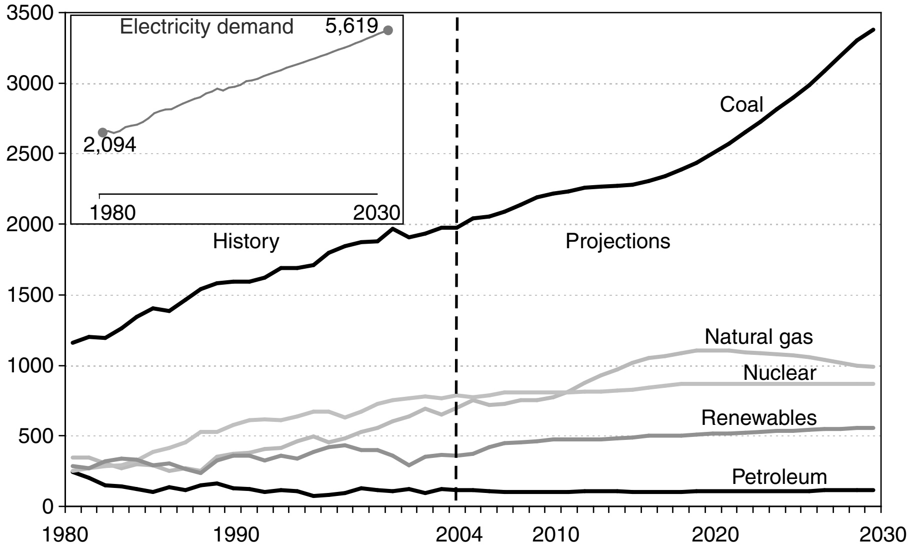

FIGURE 2.11 *AEO2006* reference case, electricity generation by fuel, 1980–2030 (billion kilowatthours).

projected growth in electricity demand and incentives for renewable, nuclear and advanced coal generation technologies leads to significantly lower levels of natural gas consumption for electricity generation. As a result, projected cumulative capacity additions and generation from natural-gas-fired power plants are lower in the *AEO2006* reference case and capacity additions and generation from coal-fired power plants are similar to the October oil futures case through 2025. In fact, in the later years of the projection, natural gas generation is expected to decline as it is displaced with generation from new coal plants (Figure 2.11).

The natural gas share of electricity generation (including generation in the end use sectors) is projected to increase from 18% in 2004 to 22% around 2020 before falling to 17% 2030. The share from coal is projected to decrease from 50% in 2004 to 49% in 2020 and then increase to 57% by 2030. In the *AEO2006* reference case, 87 GW of new coal-fired generating capacity are projected to be constructed between 2004 and 2025 (a comparable amount to the October oil futures case). Over the entire projection (2004 to 2030), 154 GW of new coal-fired generating capacity is projected to be added in the *AEO2006* reference case, including 14 GW at CTL plants.

Nuclear generating capacity in the *AEO2006* reference case is projected to increase from 99.6 GW in 2004 to 108.8 GW by 2020 (10% of total generating capacity) and remain at this level through 2030. The 9 GW increase in nuclear capacity between 2004 and 2030 consists of 3 GW of uprates of existing plants and 6 GW of new plants stimulated by provisions in *EPACT2005*. The nuclear plants that are projected to be added in 2014 and beyond will be the first new plants ordered in the United States in over 30 years. Total nuclear generation is projected to grow from 789 billion kWh in 2004 to 871 billion kWh in 2030 in the *AEO2006* reference case, but nuclear capacity in 2030 is projected to account for only about 15% of total generation.

The use of renewable technologies for electricity generation is projected to grow, stimulated both by higher fossil fuel prices and extended tax credits in the *EPACT2005* and state renewable programs. The expected impacts of state renewable portfolio standards, which specify a minimum share of generation or sales from renewable sources, are included in the projection. The *AEO2006* reference case also includes the extension and expansion of the production tax credit for wind and biomass through December 31, 2007, as enacted in the *EPACT2005*. Total renewable generation in the *AEO2006* reference case, including combined heat and power generation, is projected to grow by 1.7% per year, from 358 billion kWh in 2004 to 559 billion kWh in 2030.

In combination, the Clean Air Interstate Rule (CAIR) and the Clean Air Mercury Rule (CAMR) will lead to large reductions in pollutant emissions from power plants. In the *AEO2006* reference case, sulfur dioxide

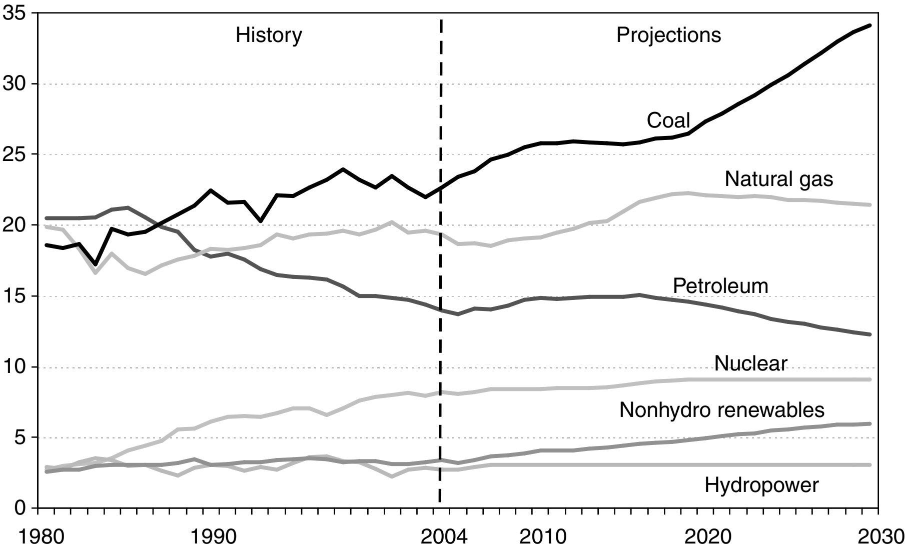

FIGURE 2.12 *AEO2006* reference case, energy production by fuel, 1980–2030 (quadrillion Btu).

emissions are 59% lower, nitrogen oxide emissions are 47% lower, and mercury emissions are 70% lower in 2025 when compared to the October oil futures case because of the inclusion of these regulations.

2.10.2.5 Energy Intensity

Energy intensity, as measured by energy use per 2000 dollar of GDP, is projected to decline at an average annual rate of 1.8% in the *AEO2006* reference case between 2004 and 2030, with efficiency gains and structural shifts in the economy dampening growth in demand for energy services. The rate of decline in energy intensity is faster than the projected 1.6% per year rate in October oil futures case between 2004 and 2025, largely because the higher energy prices in the *AEO2006* reference are projected to result in generally lower levels of energy consumption.

2.10.2.6 Energy Production and Imports

Net imports of energy on a Btu basis are projected to meet a growing share of total energy demand (Figure 2.12). In the *AEO2006* reference case, net imports are expected to constitute 32% and 33% of total U.S. energy consumption in 2025 and 2030, respectively, up from 29% in 2004, much lower then import share projected in the October oil futures case (36.5%) of *AEO2005* for 2025. The higher crude oil and natural gas prices in *AEO2006* lead to greater domestic energy production and lower demand, reducing the projected growth in imports.

In 2025, net petroleum imports, including both crude oil and refined products, are expected to account for 60% of demand (on the basis of barrels per day) in the *AEO2006* reference case compared to 66% in the October oil futures case, up from 58% in 2004. The market share of net petroleum imports grows to 60% in 2025 and 62% of demand in the *AEO2006* reference case by 2030.

Total domestic natural gas production increases from 18.5 tcf in 2004 to 21.2 tcf in 2025, before declining to 20.8 tcf in 2030 in the *AEO2006* reference case. Growth in LNG imports is projected to meet much of the increased demand for natural gas in the *AEO2006* reference case, but the increase is less than projected in the October oil futures case. The growth of LNG imports in the *AEO2006* reference case is moderated by higher domestic and imported LNG gas prices that reduce domestic natural gas demand. Because of the higher petroleum product prices, the international natural gas demand is expected to rise and raise LNG prices with it. Higher international LNG prices are projected to limit the demand for LNG demanded in the United States.

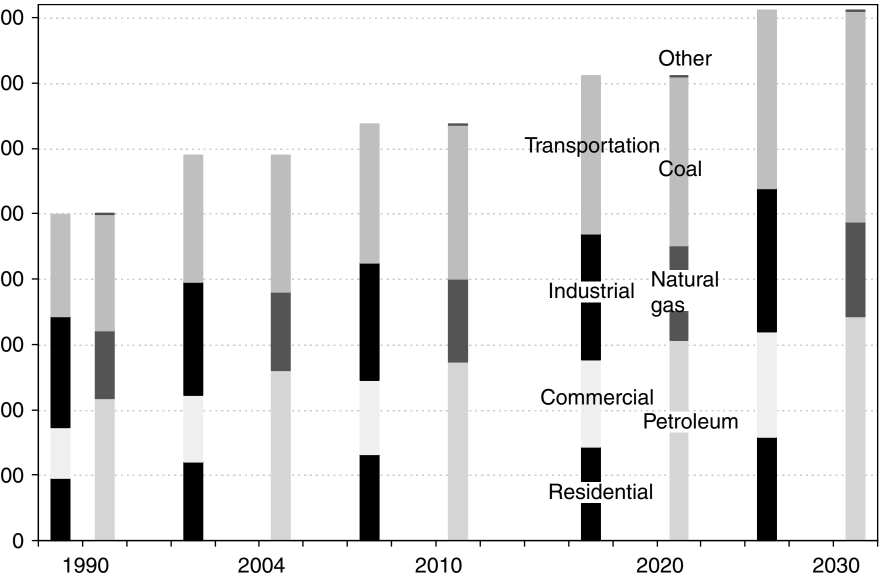

FIGURE 2.13 *AEO2006* reference case, U.S. carbon dioxide emissions by sector and fuel, 1990–2030 (million metric tons).

2.10.2.7 Carbon Dioxide Emissions

Carbon dioxide emissions from energy use are projected to increase from 5919 million metric tons in 2004 to 7587 million metric tons in 2025 and 8115 million metric tons in 2030 in the *AEO2006* reference case, an average annual increase of 1.2% per year (Figure 2.13). The carbon dioxide emissions intensity of the U.S. economy is projected to fall from 550 metric tons per million dollars of GDP in 2004 to 377 metric tons per million dollars of GDP in 2025—an average decline of 1.8% per year—and 351 metric tons per million dollars of GDP in 2030.

2.11 Overview Impacts of the AEO2006 High-Price Case*

Although short-term weather-related events (e.g., hurricanes) and geopolitical instabilities (e.g., terrorist actions and attempts by some producers to withhold supply) could raise crude oil prices well above $100 per barrel in 2004 dollars for a few months or even years, the author believes that sustained crude oil prices which exceed $75 per barrel for the next 25 years are unlikely for technical reasons.[†] Nevertheless, it is prudent to consider such a case for contingency planning purposes. This section evaluates the impacts

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*This case is provided at the request of the editor. Energy markets in the past 3 years have demonstrated the volatility of energy prices to slight supply–demand imbalances. For example, the Henry Hub spot prices have fallen from a high of over $14 per million Btu in December 2005 to a low of about $4 per million Btu in September 2006.

[†] Numerous technology and supply options for producing petroleum product substitutes are currently economically viable at prices well under $75 per barrel including: oil sands from Canada, coal-to-liquids which the Germans and South Africans used heavily (Fischer–Tropsch technology), and oil shale which was economic at about $75 per barrel using the 1980's underground mining and surface retorting process. New processes using a true in situ process are targeted to be economic at under $45 per barrel. Stranded natural gas, that is, natural gas without a currently accessible market like gas in portions of Alaska and Nigeria, could be used to economically produce high-quality petroleum products at well under $45 per barrel if the stranded natural gas price is less than $1 per thousand ft.^{3}. Biofuels for ethanol and bio-diesel are also likely to grow if high world oil prices are sustained. Finally, ultra-heavy oil, a product currently shunned by most refineries, could be economic at prices well under $75 per barrel. Given sustained high crude oil prices from conventional sources, investments in unconventional liquids production are likely to rise rapidly and eventually place downward pressure on high crude oil prices.

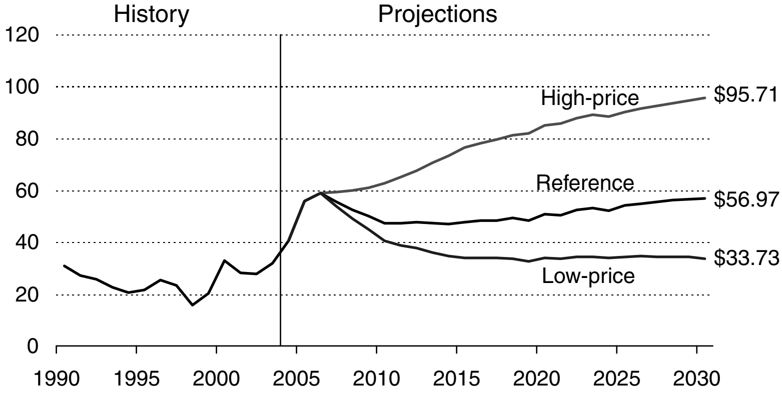

FIGURE 2.14 World oil prices (Foreign low-sulfur light crude oil prices) in three AEO2006 cases, 1990–2030 (2004 dollars per barrel). (From Energy Information Administration. *Annual outlook 2006, with projections to 2030.* DOE/EIA-0383 2006, Energy Information Administration, Washington, D.C., 2006, http://www.eia.doc.gov/oiaf/aeo/index.html)

of high oil and natural gas prices, as defined by the *Annual Energy Outlook 2006* (*AEO2006)* high-price case, on the transportation and power generation sectors of the U.S. energy economy. The *AEO2006* low-price and reference price cases are also briefly described to provide balance and context.

The *AEO2006* high- and low-price cases reflect, respectively, lower or higher domestic and international unproven/undiscovered oil and natural gas resources than the reference case. The high-price path reaches $96 per barrel in 2030 for foreign low-sulfur light crude oil (FLL) based on the assumptions that unproven/undiscovered international and domestic oil resources are 15% lower than the reference case and that the OPEC cartel adjusts its output to maintain the higher prices. In this case, the OPEC share of world oil production is projected to decline to 31% compared to over 38% in 2005. The low-price case projects that crude oil prices (FLL) will fall to about $34 per barrel in constant 2004 dollars because undiscovered oil and natural gas resources are assumed to be 15% higher than the reference case and that OPEC chooses to approximately retain its 2005 market share of about 38% through 2030[*] (see Figure 2.14).

All other things being equal, higher oil prices will stimulate more exploration and production, particularly in non-OPEC countries, and increase crude oil and alternative liquids production from oil sands, coal-to-liquids (CTL), gas-to-liquids (GTL), shale oil, ethanol, and other biofuel liquids. In addition, higher prices will reduce consumption through price-induced conservation (e.g., lower vehicle miles traveled or lower thermostat settings for space heating) and through increased efficiency uptake (e.g., more efficient cars). Table 2.3 summarizes the major outcomes of the AEO2006 price cases.

2.11.1 Domestic Oil Production

U.S. oil production is marginally sensitive to world oil prices. Higher (or lower) oil prices induce more (or less) exploration activity and the development of more (or less) oil resources. In all cases, a significant portion of total domestic oil production is projected to be produced from large, existing oil fields, such as the Prudhoe Bay Field.

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[*] OPEC's projected market share in 2030 is around 40 for the low and reference price cases. In nominal or "current-year" dollars terms, prices in 2030 will be about 70 higher than the quoted constant 2004 dollar values shown in this section. For example, a $96 dollar per barrel crude oil price (light, low sulfur) in 2004 dollars in 2030 would be over $160 per barrel in year 2030 dollars.

TABLE 2.3 AEO2006 Price Case Comparisons

		2010			2015			2020			2025			2030		
	2004	Low	Ref	High	Low	Ref	High	Low	Ref	High	Low	Ref	High	Low	Ref	High
Domestic Production																
Crude oil and lease condensate	11.47	12.71	12.45	12.24	12.69	12.37	12.20	11.77	11.75	11.91	10.56	10.56	11.22	9.51	9.68	10.50
Natural gas plant liquids	2.46	2.43	2.39	2.35	2.59	2.57	2.53	2.61	2.67	2.65	2.61	2.62	2.66	2.65	2.57	2.62
Dry natural gas	19.02	19.58	19.13	18.67	21.21	20.97	20.59	21.66	22.09	21.90	21.64	21.80	22.15	22.09	21.45	21.83
Coal	22.86	25.38	25.78	25.91	24.76	25.73	26.47	24.81	27.30	29.53	26.02	30.61	34.08	27.86	34.10	39.52
Nuclear power	8.23	8.44	8.44	8.44	8.60	8.66	8.77	9.03	9.09	9.09	9.03	9.09	9.09	9.03	9.09	9.09
Renewable energy	5.73	7.00	7.08	7.25	7.12	7.43	7.71	7.64	8.00	8.15	8.22	8.61	8.79	8.73	9.02	9.12
Other	0.64	2.13	2.16	2.20	2.90	2.85	3.01	3.04	3.16	3.37	3.10	3.32	3.74	3.15	3.44	3.91
Total	70.42	77.67	77.42	77.05	79.87	80.58	81.27	80.57	84.05	86.61	81.18	86.59	91.73	83.00	89.36	96.57
Imports																
Crude oil	22.02	22.25	22.01	21.23	24.20	22.91	21.13	27.19	24.63	22.09	30.80	26.96	23.05	33.90	29.54	24.59
Petroleum products	5.93	6.55	6.36	5.90	7.91	7.29	6.22	9.08	8.01	6.31	10.17	8.41	6.25	11.68	9.27	5.88
Natural gas	4.36	5.19	5.01	4.74	6.89	5.81	4.21	8.32	5.83	3.33	9.78	6.37	3.37	10.75	6.72	3.63
Other imports	0.83	0.45	0.45	0.46	0.73	0.74	0.98	1.49	1.36	1.61	1.97	2.02	2.17	2.09	2.42	2.69
Total	33.14	34.43	33.83	32.33	39.73	36.75	32.53	46.08	39.83	33.35	52.73	43.76	34.84	58.43	47.95	36.79
Exports																
Petroleum	2.07	2.17	2.15	2.11	2.36	2.18	2.12	2.68	2.24	2.16	2.94	2.26	2.20	2.86	2.31	2.24
Natural gas	0.86	0.57	0.55	0.53	0.66	0.58	0.48	0.83	0.68	0.50	1.10	0.86	0.58	1.35	1.01	0.57
Coal	1.25	1.03	1.03	1.03	0.54	0.54	0.54	0.46	0.46	0.46	0.48	0.48	0.45	0.39	0.40	0.40
Total	4.18	3.78	3.74	3.67	3.56	3.30	3.14	3.97	3.39	3.11	4.53	3.61	3.22	4.61	3.72	3.21
Discrepancy	−0.31	−0.32	−0.36	−0.49	−0.07	−0.16	−0.39	−0.10	−0.15	−0.24	−0.13	−0.25	−0.04	0.00	−0.30	0.07
Consumption																
Petroleum products	40.08	43.78	43.14	41.88	47.55	45.69	43.11	50.67	48.14	44.72	53.96	50.57	46.62	57.55	53.58	48.87
Natural gas	23.07	24.65	24.04	23.34	27.91	26.67	24.78	29.62	27.70	25.05	30.80	27.78	24.75	31.97	27.66	24.71
Coal	22.53	24.68	25.09	25.22	24.84	25.66	26.59	25.77	27.65	30.01	27.44	30.89	34.08	29.49	34.49	38.25
Nuclear power	8.23	8.44	8.44	8.44	8.60	8.66	8.77	9.03	9.09	9.09	9.03	9.09	9.09	9.03	9.09	9.09
Renewable energy	5.73	7.00	7.08	7.25	7.12	7.43	7.71	7.64	8.00	8.16	8.22	8.61	8.80	8.73	9.02	9.12
Other	0.04	0.07	0.07	0.08	0.08	0.08	0.09	0.04	0.05	0.06	0.05	0.05	0.05	0.05	0.05	0.05
Total	99.68	108.64	107.87	106.21	116.11	114.18	111.05	122.78	120.63	117.09	129.50	126.99	123.38	136.82	133.88	130.09

(continued)

TABLE 2.3 (*Continued*)

		2010			2015			2020			2025			2030		
	2004	Low	Ref	High	Low	Ref	High	Low	Ref	High	Low	Ref	High	Low	Ref	High
Net Imports—Petroleum	25.88	26.62	26.22	25.02	29.74	28.02	25.22	33.59	30.39	26.25	38.03	33.11	27.10	42.72	36.49	28.23
Prices (2004 dollars per unit)																
World oil price ($ per bbl)[a]	35.99	37.00	43.99	58.99	28.99	43.00	71.98	27.99	44.99	79.98	27.99	47.99	84.98	27.99	49.99	89.98
Gas wellhead price ($/mcf)	5.49	4.55	5.03	5.95	3.62	4.52	5.65	4.09	4.90	5.94	4.42	5.43	6.55	4.97	5.92	7.71
Coal minemouth price ($/ton)	20.07	21.74	22.23	22.53	19.78	20.39	21.13	19.19	20.20	21.54	19.50	20.63	21.90	20.66	21.73	22.66
Electricity (cents/kWh)	7.6	7.1	7.3	7.6	6.8	7.1	7.6	7.0	7.2	7.6	7.1	7.4	7.5	7.3	7.5	7.9
Transportation Petroleum cons																
Distillate fuel	5.91	6.90	6.82	6.71	7.61	7.48	7.25	8.25	8.13	7.90	9.08	8.95	8.78	10.10	9.98	9.93
Jet fuel	3.35	3.93	3.89	3.83	4.32	4.27	4.21	4.58	4.53	4.44	4.66	4.61	4.38	4.82	4.79	4.33
Motor gasoline[b]	16.93	18.62	18.33	17.72	20.37	19.54	18.03	21.98	20.73	18.60	23.63	21.81	19.28	25.33	22.99	20.00
Residual fuel	0.61	0.62	0.62	0.62	0.63	0.63	0.63	0.64	0.64	0.64	0.65	0.65	0.65	0.66	0.65	0.65
Liquefied petroleum gas	0.03	0.06	0.06	0.06	0.08	0.07	0.07	0.09	0.09	0.07	0.10	0.10	0.08	0.12	0.11	0.09
Other Petroleum	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.19	0.19	0.19	0.19	0.19	0.19
Petroleum subtotal	27.02	30.30	29.91	29.11	33.19	32.18	30.37	35.73	34.30	31.83	38.31	36.30	33.35	41.21	38.71	35.18
New car mpg	29.3	31.3	31.4	31.8	31.9	32.2	33.3	32.1	32.7	34.6	32.4	33.5	35.7	32.6	33.8	36.1
New light truck mpg	21.5	23.1	23.2	23.5	23.7	24.0	24.9	24.3	24.9	26.5	24.8	25.8	27.6	25.2	26.4	28.2

All energy is in quadrillion Btu. All prices are in 2004 dollars.

[a] IRAC price. Add between $4 and $7 per barrel for Imported light, low-sulfur foreign crude oil price.

[b] Ethanol as gasohol is in gasoline.

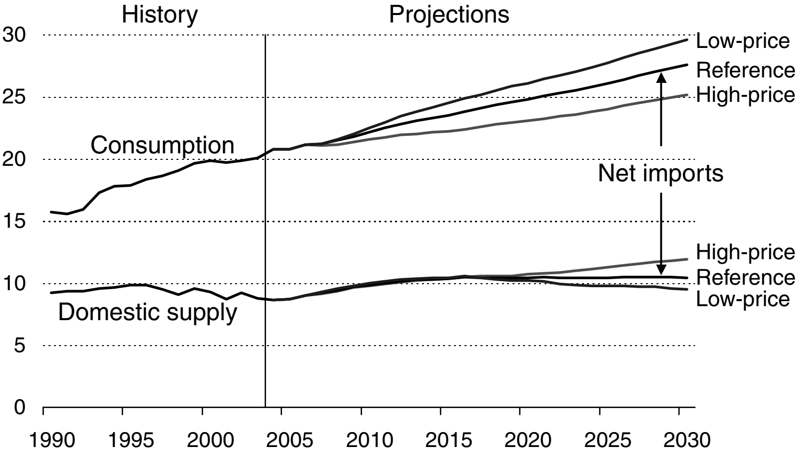

FIGURE 2.15 Petroleum supply, consumption, and imports in AEO2006 1990–2030 (million barrels per day).

In the high-price case, FLL crude oil prices in 2030 are 68% higher than the reference case and yield only 9% higher domestic production because of the smaller resource base. Domestic liquids consumption is 9% lower because of the higher prices.

2.11.2 Impacts of High World Oil Prices on Oil Imports

Oil import dependence is sensitive to world oil prices. In the low-price case, imported oil is projected to grow from a 58% share of total oil supply in 2004 to 68% in 2030; the reference and high-price cases project imported oil shares to be 62% and 53%, respectively. In the reference case, net oil imports are expected to rise from a little over 12 million barrels per day in 2004 to over 17 million barrels per day in 2030. In the low-price case, oil imports in 2030 are expected to rise above 20 million barrels per day. The high-price case is expected to moderate demand so that oil imports are expected to remain near 2005's level, about 13 million barrels per day (see Figure 2.15).

As in the United States, projected oil prices directly affect world oil consumption: higher projected oil prices result in lower projected world oil consumption. In the reference case, world oil consumption is projected to rise from about 82.5 million barrels per day in 2004 to about 118 million barrels per day in 2030, whereas world oil consumption is expected to be 128 and 102 million barrels per day in the low- and high-price cases, respectively.

2.11.3 Impacts of High World Oil Prices on Domestic Unconventional Liquids Supply

High world oil prices provide economic incentives for the development of unconventional liquids technologies. Gas-to-liquids (GTL) plants are projected to be built on the Alaskan North Slope in the high-price case to convert stranded gas to zero-sulfur distillates to be transported via the Trans-Alaska pipeline to Valdez and shipped to the lower-48 states for use on the west coast. GTL production is expected to be economic and reach 200,000 barrels per day in 2030 only in the high-priced case because access to inexpensive Alaskan natural gas supplies are expected to be committed to the Alaska natural gas pipeline that is expected to be completed by 2015.

Coal-to-liquids (CTL) plants are projected to be built in the lower-48 states for the reference and high-price cases. Full-scale CTL production is projected to start in 2011 in both the reference and high-price cases, reaching just under 800,000 barrels per day in 2030 in the reference case and about 1.7 million

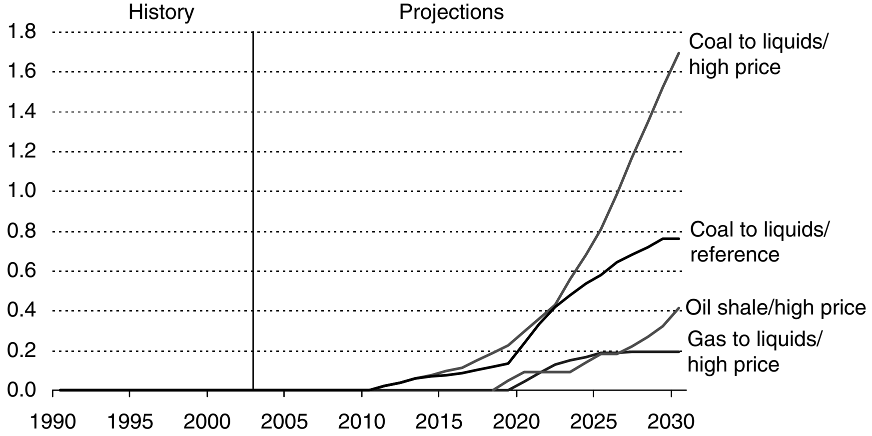

FIGURE 2.16 Gas-to-liquids, coal-to-liquids, and oil shale production in the price cases, 1990–2030 (million barrels per day).

barrels per day in the high-price case (see Figure 2.16). Major environmental and water uncertainties may affect the potential growth of CTL plant investments.

Production costs for oil shale syncrude are even more uncertain than CTL production costs.* Development of this domestic resource came to a halt in the mid-1980s, during a period of low oil prices. The cost assumptions used in developing the *AEO2006* projections represent an oil shale industry based on underground mining and surface retorting. However, the development of a true in situ retorting technology could substantially reduce the cost of producing oil shale syncrude and possibly make its production economic in the reference case. Oil shale production is not economic in the low-price and reference cases of *AEO2006* but is expected to become economic around 2020 in the high-price case; oil shale production is projected to steadily rise to over 400,000 barrels per day by 2030 (see Figure 2.16).

2.11.4 Impacts of High World Oil Prices on Ethanol Production

The Energy Policy Act of 2005 (EPAct 2005) requires that ethanol be used for gasoline-based transportation and rise to at least 7.5 billion gallons by 2012. Consumption is required to rise proportionately with gasoline consumption thereafter. World oil prices are high enough in all of the *AEO2006* price cases to exceed the minimum levels required by the law. Ethanol consumption in 2012 is projected to be between 9.6 and 9.9 billion gallons in the three price cases and rise to consumption levels between 11 and 15 billion gallons in 2030 (see Figure 2.17). As expected, the highest gasoline prices encourage the highest ethanol consumption. Almost all of the ethanol is projected to be produced from corn, with only small amounts of cellulosic ethanol expected to penetrate the market (250 million gallons per year) because of EPAct 2005 incentives. Capital costs reductions and breakthroughs in the cost of manufacturing the enzyme needed for cellulosic ethanol conversion could alter the competitive outlook for cellulosic ethanol.

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*The United States has more than half of the world's undiscovered recoverable oil shale resources. The U.S. government has not funded any significant new research in oil shale since the early 1980s when the oil shale technologies were estimated to become economic at prices in the $70 to $80 per barrel range. New leases on prime oil shale lands and current pilot project plans and lease bids on oil shale using new approaches by the Shell Oil Corporation, among others, will provide better information and will hopefully identify lower-cost applications of technologies and processes for producing syncrude from oil shale.

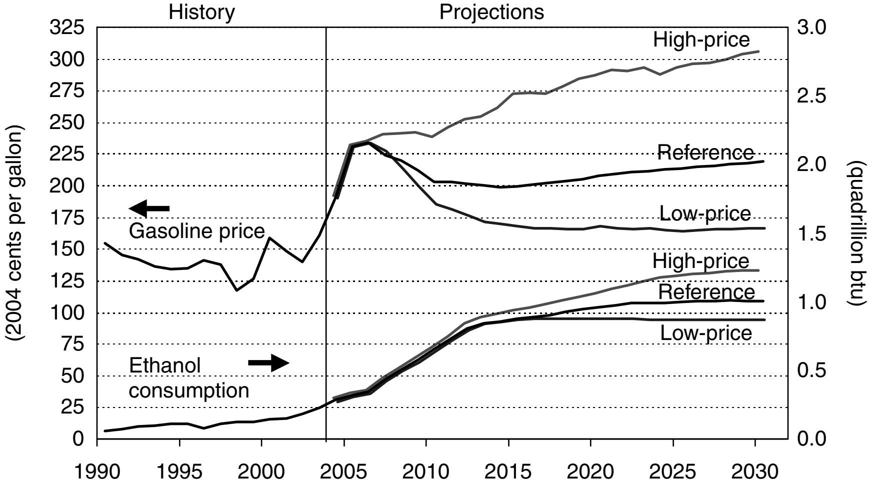

FIGURE 2.17 *AEO2006* ethanol consumption and gasoline price in transportation sector, 1990–2030.

2.11.5 LNG Imports are the Source of Natural Gas Supply Most Affected in the Price Cases

Higher world oil prices are expected to result in a shift away from petroleum consumption and toward natural gas and coal consumption in all sectors of the international energy market. LNG prices are expected to roughly follow the pattern of world crude oil prices because many LNG contract prices are tied directly to crude oil prices and higher oil prices are expected to promote increased GTL production. Both of these factors are expected to put upward price pressure on world natural gas supplies. Because of the higher LNG prices in the high-price case, it is expected that U.S. LNG imports, new LNG receiving capacity, and the utilization rates for LNG terminals will be lower than the reference case.

Net imports of LNG in the reference case are 4.4 trillion ft.^{3} in 2030. In the low-price case, net LNG imports increase to 7.4 trillion ft.^{3}, and in the high-price case they fall to 1.9 trillion ft.^{3} (see Figure 2.18).

2.11.6 Natural Gas Wellhead Prices

In all three *AEO2006* price cases, projected wellhead natural gas prices are projected to decline from current levels, reach a low point around 2015, and subsequently rise (see Figure 2.19).

The relatively high projected natural gas prices, particularly in the reference case, both expand the development of new gas supplies, particularly of LNG and Alaska gas, while also constraining future gas consumption growth. Collectively, the interaction of greater gas supply and slower gas demand growth leads to the projected decline in gas prices through roughly 2015 in all three cases. Natural gas from Alaska is projected to be economic in all *AEO2006* price cases by about 2015.

After 2015, natural gas prices are projected to rise again as the increasing marginal costs of developing the remaining U.S. natural gas resources increase. As domestic natural gas resources are produced, the remaining gas resources are more costly and riskier to develop and produce.

In the reference case, the projected wellhead natural gas price is projected to increase from about \$4.45 per thousand ft.^{3} in 2016 to about \$5.90 per thousand ft.^{3} (2004 dollars) in 2030. Because the low- and high-price cases respectively increased or reduced domestic unproven gas resources by 15%, natural gas prices in 2030 are projected to be about \$5 per thousand ft.^{3} in the low-price case and \$7.70 per thousand ft.^{3} in the high-price case.

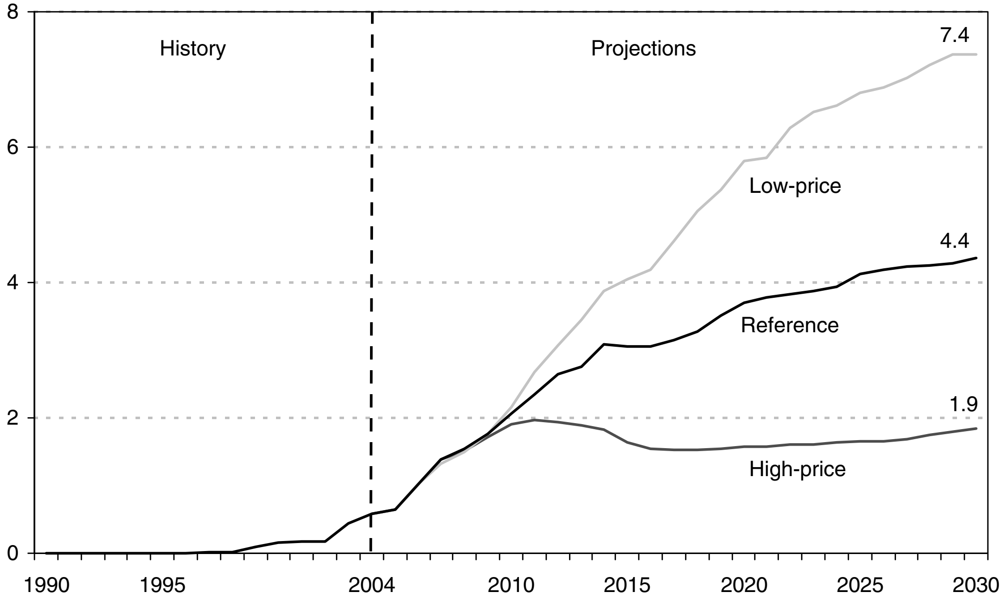

FIGURE 2.18 Net imports of liquefied natural gas in three cases, 1990–2030 (trillion ft.^{3}).

2.11.7 Petroleum Demand Is Significantly Lower in the High-Price Case

Petroleum demand in 2030 in the high-price case is projected to be about 2.4 million barrels per day lower than the reference case. Petroleum imports in 2030 are expected to be roughly comparable to 2005 import levels. Most of the petroleum reduction in the high-price case occurs in gasoline consumption by light-duty vehicles (cars and light trucks). Gasoline consumption in the high-price case is projected to be about 1.5 million barrels per day lower than the reference case in 2030 (see Figure 2.20).

Motor gasoline consumption is driven by vehicle miles traveled and efficiency uptake. High oil prices reduce personal disposable income, which lowers vehicle miles traveled and increases the adoption of more efficient transportation technologies.

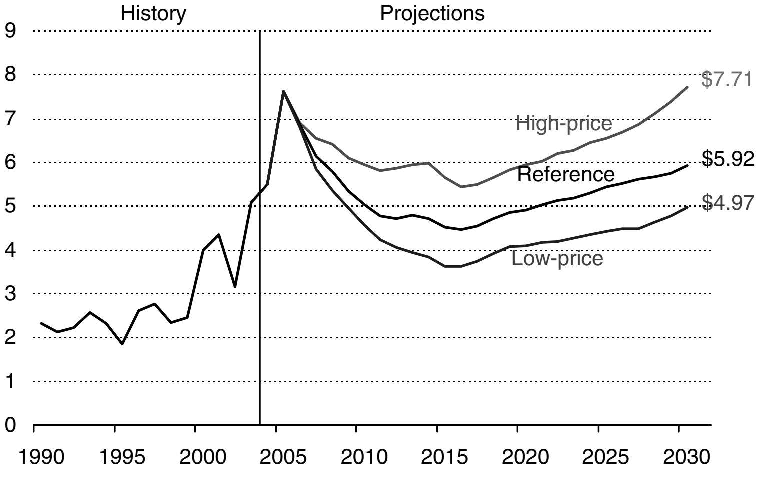

FIGURE 2.19 Natural gas wellhead prices, 1990–2030 (2004 dollars per thousand ft.^{3}).

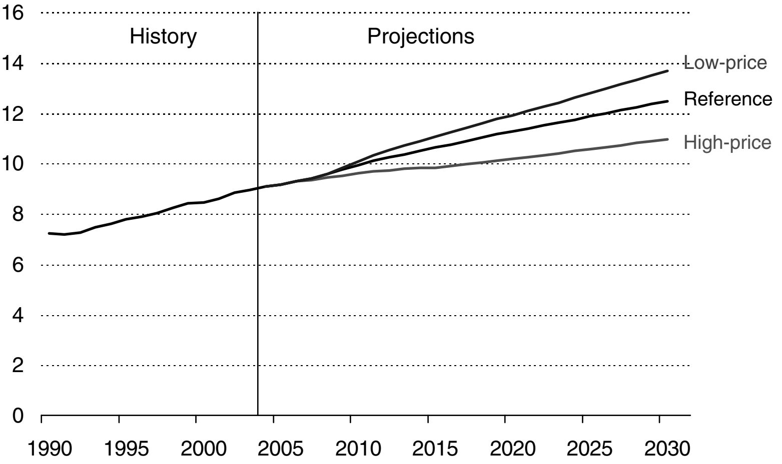

FIGURE 2.20 Motor gasoline consumption, 1990–2030 (million barrels per day).

- Gasoline consumption is expected to rise from 9.1 million barrels per day in 2004 to 13.7, 12.5, and 11.0 million barrels per day in the low-price, reference, and high-price cases, respectively, in 2030.
- Vehicle miles traveled by light-duty vehicles is projected to rise from 2.6 trillion miles in 2005 to 4.4, 4.1, and 3.9 trillion miles in the low-price, reference, and high-price cases, respectively, in 2030.
- New car vehicle efficiency is projected to rise from 29.3 in 2004 to 32.6, 33.8, and 36.1 miles per gallon in the reference case in 2030 (see Figure 2.21).
- Three of the most promising transportation technologies are advanced drag reduction, variable valve timing, and extension of four valves per cylinder technology to six valves per cylinder engines. Each of these would provide more than an 8% boost to fuel economy.

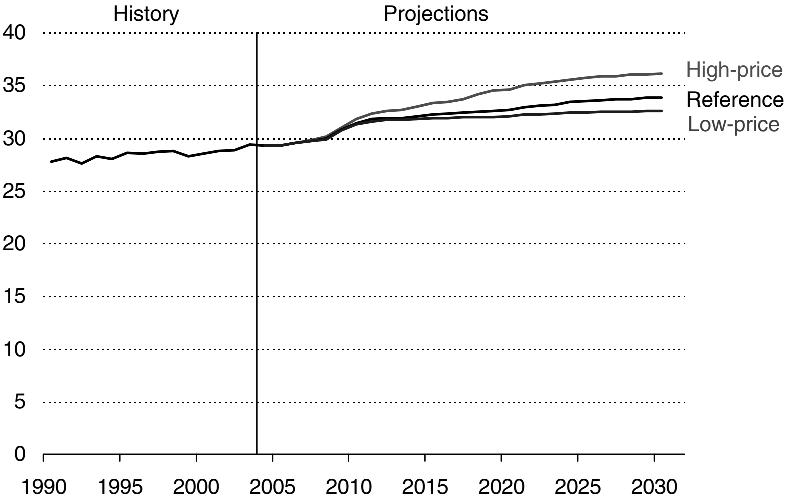

FIGURE 2.21 New car miles per gallon, 1990–2030.

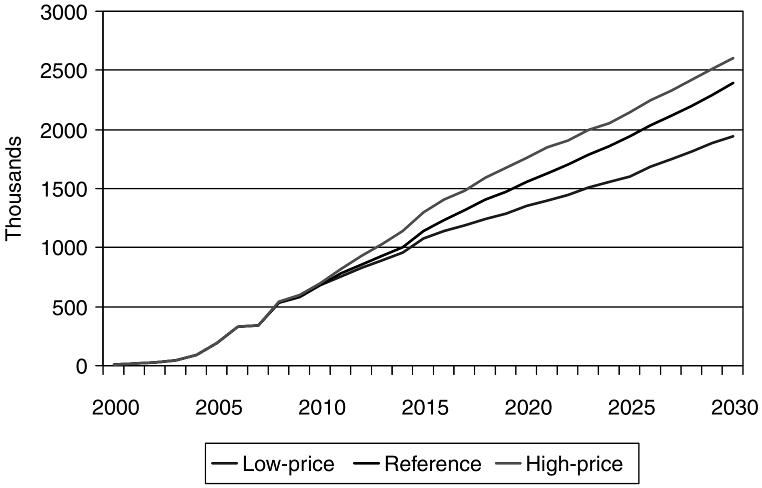

FIGURE 2.22 Hybrid vehicle annual fuel savings.

2.11.8 EPAct2005 Accelerates the Early Adoption of Hybrid Vehicles

EPAct2005 provides financial incentives for the early adoption of hybrid vehicles prior to 2010. Those incentives are projected to accelerate the adoption of hybrid fuel vehicles and help reduce the incremental vehicle costs for midsize full hybrid vehicles from about $2500 in 2005 to about $1500 by 2015. However, because the incentives are limited to the first 60,000 sales by each manufacturer and based on the relative efficiency improvements, the relative impacts are also limited. After 2010, hybrid adoption loses its EPAact 2005 incentives. In the high-price case, fuel savings for a typical midsize car are approximately $300 per year while the savings are reduced to about $225 per year in the reference case and to under $200 per year in the low-price case (see Figure 2.22).

The projected energy savings between the price cases are not sufficiently large, however, to drastically change the hybrid vehicle adoptions by 2030. Hybrid vehicle sales are projected to increase from about 92

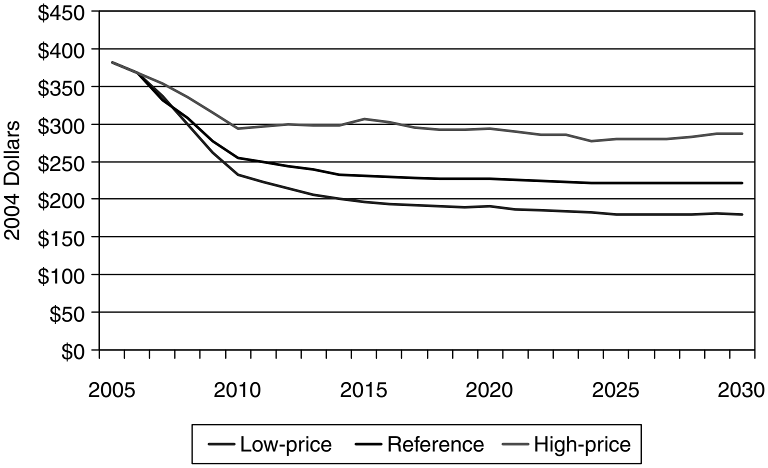

FIGURE 2.23 Hybrid vehicle sales.

thousand in 2004 to about 2.4 million in 2030 in the reference case, 2.6 million in the high-price case, and 1.9 million in the low-price case. With faster hybrid penetration, vehicle costs decline due to manufacturer learning, which leads to greater adoption (see Figure 2.23). Hybrids like the Prius can be viewed as full hybrids and the less aggressive types with the integrated starter generator (ISG), no power assist, like those made by GM are called *mild hybrids*. Full hybrids are expected to represent about 80% of the hybrid sales by 2030.

2.11.9 High Oil and Gas Prices Increase Coal-Based Generation

The U.S. power generation industry is projected to increasingly rely on coal-based generation as natural gas prices increase. Of the four major gas consumption sectors (residential, commercial, industrial, and electric power), the electric power sector's consumption of natural gas is the most affected by natural gas prices over time.

Gas-fired generation facilities can operate in the base, intermediate, and peaking portions of the electricity load duration curve. As gas prices become increasingly more expensive, the operating costs become a more important factor in making the capacity addition and dispatch decisions. With higher natural gas prices, an increasing proportion of new electricity generators are projected to be coal-fired facilities, which are placed in preference to gas-fired facilities in the load duration curve, thereby displacing gas-fired generators from operating in the base and later in the intermediate-load portions of the load duration curve, limiting their operation mostly to the peaking portion of the curve.

In the reference case, electricity sector gas consumption is projected to grow from 5.3 trillion ft.^{3} in 2004 to 6.4 trillion ft.^{3} in 2030. In comparison, electric power sector is projected to consume 9.9 and 4.1 trillion ft.^{3} in the low- and high-price cases, respectively, in 2030.

Figure 2.24 illustrates that steam coal facility construction increases at higher natural gas prices, thereby reducing the level of gas-fired capacity by 2030 relative to the *AEO2006* reference case. In the reference case, combined cycle gas-fired facilities increase from 159 GW in 2004 to 231 GW in 2030. In the high-price case, gas-fired combined cycle capacity only grows to 191 GW in 2030, while the low-price case projects 281 GW of gas-fired combined cycle capacity.

Most of the reduction in gas-fired electricity generator construction in the high gas price case is compensated by an increase in coal-fired electricity generation facilities. In the reference case, coal-fired steam capacity grows from 310 GW in 2004 to 457 GW in 2030. In the low- and high-price cases, coal-fired steam capacity is projected to be 380 and 509 GW, respectively.

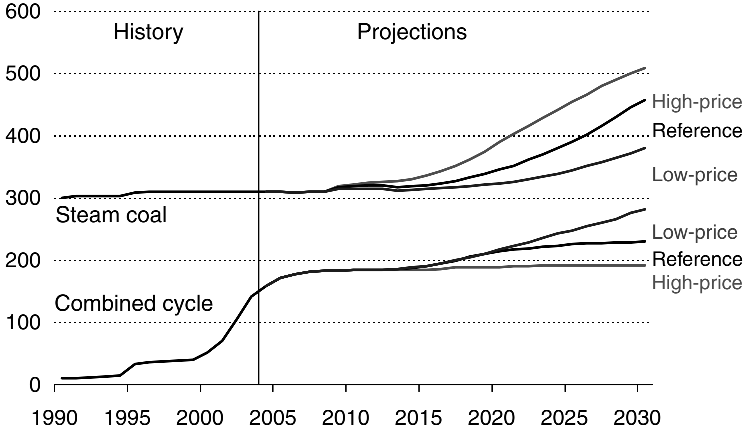

FIGURE 2.24 Generation capacity from steam coal and combined cycle, 1990-2030 (GW).

Acknowledgments

I am indebted to the forecasting staff of the Office of Integrated Analysis and Forecasting in the Energy Information Administration (EIA) for their integral part in helping to develop this projection. Credits for this effort are shared with the staff and management who produced the *Annual Energy Outlook 2005* (*AEO2005*) and the updated reference case forecast in the *Annual Outlook 2006* (*AEO2006*) which is summarized in the last section of this chapter. The *AEO2006* reference case was released to the public on December 12, 2005 on the EIA website and the complete publication in February, 2006. Like all projections, *these projections represent what might occur under laws, regulations, policies, and other key assumptions of the scenarios at the time of their development, not what will occur*. All errors remain the sole responsibility of this author.

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3

Economics Methods

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3.1 Introduction

Economic-evaluation methods facilitate comparisons among energy technology investments. Generally, the same methods can be used to compare investments in energy supply or energy efficiency. All sectors of the energy community need guidelines for making economically efficient energy-related decisions.

This chapter provides an introduction to some basic methods that are helpful in designing and sizing cost-effective systems, and in determining whether it is economically efficient to invest in specific energy efficiency or renewable energy projects. The targeted audience includes analysts, architects, engineers, designers, builders, codes and standards writers, and government policy makers—collectively referred to as the *design community*.

The focus is on microeconomic methods for measuring cost-effectiveness of individual projects or groups of projects, with explicit treatment of uncertainty. The chapter does not treat macroeconomic methods and national market-penetration models for measuring economic impacts of energy efficiency and renewable energy investments on the national economy. It provides sufficient guidance for computing measures of economic performance for relatively simple investment choices, and it provides the fundamentals for dealing with complex investment decisions.

3.2 Making Economically Efficient Choices[1]

Economic-evaluation methods can be used in a number of ways to increase the economic efficiency of energy-related decisions. There are methods that can be used to obtain the largest possible savings in energy costs for a given energy budget; there are methods that can be used to achieve a targeted reduction in energy costs for the lowest possible efficiency/renewable energy investment; and there are methods that can be used to determine how much it pays to spend on energy efficiency and renewable energy to lower total lifetime costs, including both investment costs and energy cost savings.

The first two ways of using economic-evaluation methods (i.e., to obtain the largest savings for a fixed budget and to obtain a targeted savings for the lowest budget) are more limited applications than the third, which aims to minimize total costs or maximize NB (net savings) from expenditure on energy efficiency and renewables. As an example of the first, a plant owner may budget a specific sum of money for the purpose of retrofitting the plant for energy efficiency. As an example of the second, designers may be required by state or federal building standards and/or codes to reduce the design energy loads of new buildings below some specified level. As an example of the third, engineers may be required by their clients to include, in a production plant, those energy efficiency and renewable energy features that will pay off in terms of lower overall production costs over the long run.

Note that economic efficiency is not necessarily the same as engineering thermal efficiency. For example, one furnace may be more "efficient" than another in the engineering technical sense, if it delivers more units of heat for a given quantity of fuel than another. Yet it may not be economically efficient if the first cost of the higher-output furnace outweighs its fuel savings. The focus in this chapter is on economic efficiency, not technical efficiency.

Economic efficiency is illustrated conceptually in Figure 3.1 through Figure 3.3 with an investment in energy efficiency. Figure 3.1 shows the level of energy conservation, Q_c, that maximizes NB from energy conservation, i.e., the level that is most profitable over the long run. Note that it is the point at which the curves are most distant from one another.

Figure 3.2 shows how "marginal analysis" can be used to find the same level of conservation, Q_c, that will yield the largest NB. It depicts changes in the total benefits and cost curves (i.e., the derivatives of the curves in Figure 3.1) as the level of energy conservation is increased. The point of intersection of the marginal curves coincides with the most profitable level of energy conservation indicated in Figure 3.1. This is the point at which the cost of adding one more unit of conservation is just equal to the corresponding benefits in terms of energy savings (i.e., the point at which "marginal costs" and "marginal benefits" are equal). To the left of the point of intersection, the additional benefits from increasing the level of conservation by another unit are greater than the additional costs, and it pays to invest more. To the right of the point of intersection, the costs of an addition to the level of conservation exceed the benefits and the level of total NB begins to fall, as shown in Figure 3.1. Figure 3.3 shows that the most economically efficient level of energy conservation, Q_c, is that for which the total cost curve is at a minimum.

The most economically efficient level of conservation, Q_c, is the same in Figure 3.1 through Figure 3.3. Three different approaches to finding Q_c are illustrated: (1) finding the maximum difference between

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[1] This section is based on a treatment of these concepts provided by Marshall and Ruegg in *Economics of Solar Energy and Conservation Systems*, Kreith and West, ed., CRC Press, 1980.

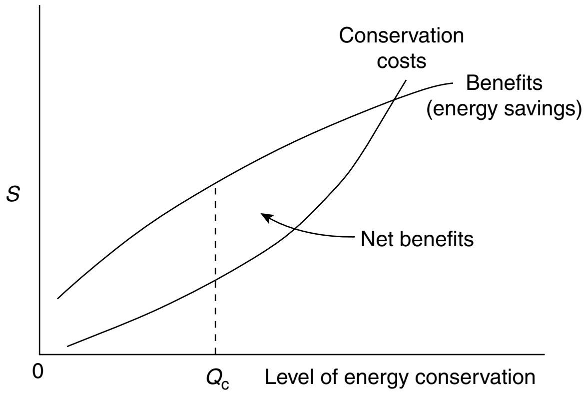

FIGURE 3.1 Maximizing net benefits.

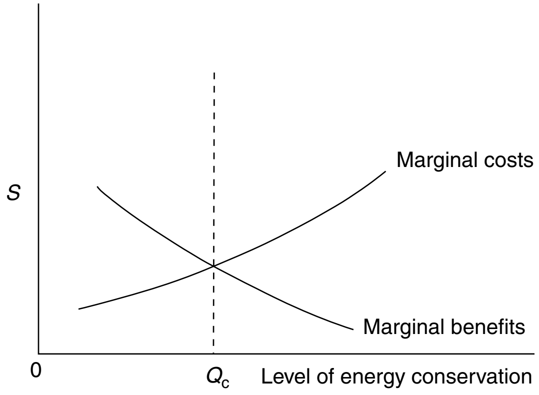

FIGURE 3.2 Equating marginal benefits and marginal costs.

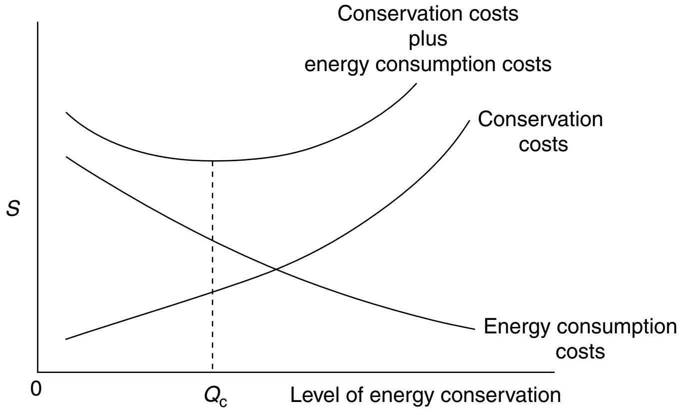

FIGURE 3.3 Minimizing life-cycle costs.

benefits and costs, (2) finding the point where marginal benefits equal marginal costs, and (3) finding the lowest life-cycle costs (LCCs).

3.3 Economic-Evaluation Methods[2]

There are a number of closely related, commonly used methods for evaluating economic performance. These include the LCC method, levelized cost of energy, NB (net present worth) method, benefit-cost (or savings-to-investment) ratio method, internal rate-of-return method, overall rate-of-return method, and payback method. All of these methods are used when the important effects can be measured in dollars. If incommensurable effects are critical to the decision, it is important that they also be taken into account. But, because only quantified effects are included in the calculations for these economic methods, unquantified effects must be treated outside the models. Brief treatments of the methods are provided; some additional methods are identified but not treated. For more comprehensive treatments, see Ruegg and Marshall (1990) and other sources listed at the end of the chapter.

3.3.1 Life-Cycle Cost Method

The life-cycle costing (LCC) method sums, for each investment alternative, the costs of acquisition, maintenance, repair, replacement, energy, and any other monetary costs (less any income amounts, such as salvage value) that are affected by the investment decision. The time value of money must be taken into account for all amounts, and the amounts must be considered over the relevant period. All amounts are usually measured either in present value or annual value dollars. This is discussed later under "Discounting" and "Discount Rate." At a minimum, for comparison, the investment alternatives should include a "base-case" alternative of not making the energy efficiency or renewable investment, and at least one case of an investment in a specific efficiency or renewable system. Numerous alternatives may be compared. The alternative with the lowest LCC that meets the investor's objective and constraints is the preferred investment.

Following is a formula for finding the LCCs of each alternative:

$$\mathrm{LCC}_{\mathrm{A1}} = I_{\mathrm{A1}} + E_{\mathrm{A1}} + M_{\mathrm{A1}} + R_{\mathrm{A1}} - S_{\mathrm{A1}}, \tag{3.1}$$

where $\mathrm{LCC}_{\mathrm{A1}}$ is the life-cycle cost of alternative Al, I_{A1} is the present-value investment costs of alternative A1, E_{A1} is the present-value energy costs associated with alternative A1, M_{A1} is the present-value nonfuel operating and maintenance cost of A1, R_{A1} is the present-value repair and replacement costs of A1, and S_{A1} is the present-value resale (or salvage) value less disposal cost associated with alternative A1.

The LCC method is particularly useful for decisions that are made primarily on the basis of cost effectiveness, such as whether a given energy efficiency or renewable energy investment will lower total cost, (e.g., the sum of investment and operating costs). It can be used to compare alternative designs or sizes of systems, as long as the systems provide the same service. The method, if used correctly, can be used to find the overall cost-minimizing combination of energy efficiency investments and energy supply investments within a given facility. However, in general, it cannot be used to find the best investment, because totally different investments do not provide the same service.

3.3.2 Levelized Cost of Energy

The levelized cost of energy (LCOE) is similar to the LCC method, in that it considers all the costs associated with an investment alternative and takes into account the time value of money for the analysis period. However, it is generally used to compare two alternative energy supply technologies or systems,

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[2] These methods are treated in detail in Ruegg and Marshall *Building Economics: Theory and Practice*, Chapman and Hall, New York, NY, 1990.

e.g., two electricity production technologies. It differs from the LCC in that it usually considers taxes, but like LCC, it frequently ignores financing costs.

The LCOE is the value that must be received for each unit of energy produced to ensure that all costs and a reasonable profit are made. Profit is ensured by discounting future revenues at a discount rate that equals the rate of return that might be gained on other investments of comparable risk, i.e., the opportunity cost of capital. In equation form, this is represented as:

$$\sum_{t=1}^{t=N} \mathrm{LCOE} * Q_t/(1+d')^t = \sum_{t=0}^{t=N} C_t/(1+d)^t, \tag{3.2}$$

where N is the analysis period, Q_t is the amount of energy production in period t, C_t is the cost incurred in period t, d' is the discount rate or opportunity cost of capital. If d' is a real discount rate (excludes inflation) then the LCOE will be in real (constant) dollar terms, whereas the LCOE will be in nominal (current) dollar terms if d' is a nominal discount rate. The discount rate, d, is used to bring future costs back to their present value. If those costs are expressed in real dollars, then the discount rate should be a real discount rate; if they are in nominal dollars, the discount rate should be a nominal discount rate.

3.3.3 Net Present Value or Net Benefits Method

The net present value (NPV) method finds the excess of benefits over costs, where all amounts are discounted for their time value. (If costs exceed benefits, net losses result.)

The NPV method is also often called the *net present worth* or *net savings* method. When this method is used for evaluating a cost-reducing investment, the cost savings are the benefits, and it is often called the *net savings* (NS) method.

Following is a formula for finding the NPV from an investment, such as an investment in energy efficiency or renewable energy systems:

$$\mathrm{NPV}_{\mathrm{A1:A2}} = \sum_{t=0}^{N} \frac{(B_t - C_t)}{(1+d)^t}, \tag{3.3}$$

where $\mathrm{NPV}_{\mathrm{A1:A2}}$ is NB, i.e., present value benefits (savings) net of present value costs for alternative A1 as compared with alternative A2, B_t is benefits in year t, which may be defined to include energy savings, C_t is costs in year t associated with alternative A1 as compared with a mutually exclusive alternative A2, and d is the discount rate.

The NPV method is particularly suitable for decisions made on the basis of long-run profitability. The NPV (NB) method is also useful for deciding whether to make a given investment and for designing and sizing systems. It is not very useful for comparing investments that provide different services.

3.3.4 Benefit-to-Cost Ratio or Savings-to-Investment Ratio Method

The benefit-to-cost ratio (BCR) or savings-to-investment ratio (SIR) method divides benefits by costs or by savings by investment. When used to evaluate energy efficiency and renewable energy systems, benefits are in terms of energy cost savings. The numerator of the SIR ratio is usually constructed as energy savings, net of maintenance and repair costs; and the denominator as the sum of investment costs and replacement costs less salvage value (capital cost items). However, depending on the objective, sometimes only initial investment costs are placed in the denominator and the other costs are subtracted in the numerator—or sometimes only the investor's equity capital is placed in the denominator. As with the three preceding methods, this method is based on discounted cash flows.

Unlike the three preceding methods that provided a performance measure in dollars, this method gives the measure as a dimensionless number. The higher the ratio, the more dollar savings realized per dollar of investment.

Following is a commonly used formula for computing the ratio of savings-to-investment costs:

$$\mathrm{SIR}_{\mathrm{A1:A2}} = \frac{\sum_{t=0}^{N}[\mathrm{CS}_t(1+d)^{-t}]}{\sum_{t=0}^{N}(I_t(1+d)^{-t})}, \tag{3.4}$$

where $\mathrm{SIR}_{\mathrm{A1:A2}}$ is the SIR for alternative A1 relative to mutually exclusive alternative A2, CS_t is the cost savings (excluding those investment costs in the denominator) plus any positive benefits of alternative A1 as compared with mutually exclusive alternative A2, and I_t is the additional investment costs for alternative A1 relative to A2.

Note that the particular formulation of the ratio with respect to the placement of items in the numerator or denominator can affect the outcome. One should use a formulation appropriate to the decision maker's objectives.

The ratio method can be used to determine whether or not to accept or reject a given investment on economic grounds. It also can be used for design and size decisions and other choices among mutually exclusive alternatives, if applied incrementally (i.e., the investment and savings are the difference between the two mutually exclusive alternatives). A primary application of the ratio method is to set funding priorities among projects competing for a limited budget. When it is used in this way—and when project costs are "lumpy" (making it impossible to fully allocate the budget by taking projects in order according to the size of their ratios)—SIR should be supplemented with the evaluation of alternative sets of projects using the NPV or NB method.

3.3.5 Internal Rate-of-Return Method

The internal rate-of-return (IRR) method solves for the discount rate for which dollar savings are just equal to dollar costs over the analysis period; that is, the rate for which the NPV is zero. This discount rate is the rate of return on the investment. It is compared to the investor's minimum acceptable rate of return to determine whether the investment is desirable. Unlike the preceding three techniques, the internal rate of return does not call for the inclusion of a prespecified discount rate in the computation; rather, it solves for a discount rate.

The rate of return is typically calculated by a process of trial and error, by which various compound rates of interest are used to discount cash flows until a rate is found for which the NPV of the investment is zero. The approach is the following: (1) Compute *NPV* using Equation 3.3, except substitute a trial interest rate for the discount rate, d, in the equation. A positive NPV means that the IRR is greater than the trial rate; a negative NPV means that the IRR is less than the trial rate. (2) Based on the information, try another rate. (3) By a series of iterations, find the rate at which NPV equals zero.

Computer algorithms, graphical techniques, and—for simple cases—discount-factor tabular approaches, are often used to facilitate IRR solutions (Ruegg and Marshall 1990:7172). Expressing economic performance as a rate of return can be desirable for ease in comparing the returns on a variety of investment opportunities, because returns are often expressed in terms of annual rates of return. The IRR method is useful for accepting or rejecting individual investments or for allocating a budget. For designing or sizing projects, the IRR method, like the SIR, must be applied incrementally. It is not recommended for selecting between mutually exclusive investments with significantly different lifetimes (e.g., a project with a 35% return for 20 years is a much better investment than a project with the same 35% return for only two years).

It is a widely used method, but it is often misused, largely due to shortcomings that include the possibility of:

- No solution (the sum of all nondiscounted returns within the analysis period are less than the investment costs)
- Multiple solution values (some costs occur later than some of the returns)

- Failure to give a measure of overall return associated with the project over the analysis period (returns occurring before the end of the analysis are implicitly assumed to be reinvested at the same rate of return as the calculated IRR; this may or may not be possible)

3.3.6 Overall Rate-of-Return Method

The overall rate-of-return (ORR) method corrects for the last two shortcomings expressed above for the IRR. Like the IRR, the ORR expresses economic performance in terms of an annual rate of return over the analysis period. But unlike the IRR, the ORR requires, as input, an explicit reinvestment rate on interim receipts and produces a unique solution value.[3] The explicit reinvestment rate makes it possible to express net cash flows (excluding investment costs) in terms of their future value at the end of the analysis period. The ORR is then easily computed with a closed-form solution as shown in Equation 3.5:

$$\mathrm{ORR}_{\mathrm{A1:A2}} = \frac{\left[\sum_{t=0}^{N}(B_t - C_t)(1+r)^{N-t}\right]^{1/N}}{\left[\sum_{t=0}^{N} I_t/(1+r)^t\right]^{1/N}} - 1, \tag{3.5}$$

where $\mathrm{ORR}_{\mathrm{A1:A2}}$ is the overall rate of return on a given investment alternative A1 relative to a mutually exclusive alternative over a designated study period, B_t represents the benefits from a given alternative relative to a mutually exclusive alternative A2 over time period t, C_t is the costs (excluding that part of investment costs on which the return is to be maximized) associated with a given alternative relative to a mutually exclusive alternative A2 over time t, r is the reinvestment rate at which net returns can be reinvested, usually set equal to the discount rate, N is the length of the study period, and I_t represents the investment costs in time t on which the return is to be maximized.

The ORR is recommended as a substitute for the IRR, because it avoids some of the limitations and problems of the IRR. It can be used for deciding whether or not to fund a given project, for designing or sizing projects (if it is used incrementally), and for budget-allocation decisions.

3.3.7 Discounted Payback Method

This evaluation method measures the elapsed time between the time of an initial investment and the point in time at which accumulated discounted savings or benefits—net of other accumulated discounted costs—are sufficient to offset the initial investment, taking into account the time value of money. (If costs and savings are not discounted, the technique is called "simple payback.") For the investor who requires a rapid return of investment funds, the shorter the length of time until the investment pays off, the more desirable the investment.

To determine the discounted payback method (DPB) period, find the minimum value of Y (year in which payback occurs) such that the following equality is satisfied.

$$\sum_{t=1}^{Y}(B_t - C'_t)/(1+d)^t = I_0, \tag{3.6}$$

where B_t represents the benefits associated in period t with one alternative as compared with a mutually exclusive alternative, C'_t is the costs in period t (not including initial investment costs) associated with an alternative as compared with a mutually exclusive alternative in period t, and I_0 is the initial investment

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[3] As shown in Equation 3.5, the reinvestment rate is also used to bring all investments back to their present value. Alternatively, investments after time zero can be discounted by the overall growth rate. In this case, a unique solution is not guaranteed, and the ORR must be found iteratively (Stermole and Stermole 2000).

costs of an alternative as compared with a mutually exclusive alternative, where the initial investment cost comprises total investment costs.

DPB is often (correctly) used as a supplementary measure when project life is uncertain. It is used to identify feasible projects when the investor's time horizon is constrained. It is used as a supplementary measure in the face of uncertainty to indicate how long capital is at risk. It is a rough guide for accept/reject decisions. It is also overused and misused. Because it indicates the time at which the investment just breaks even, it is not a reliable guide for choosing the most profitable investment alternative, as savings or benefits after the payback time could be significant.

3.3.8 Other Economic-Evaluation Methods

A variety of other methods have been used to evaluate the economic performance of energy systems, but these tend to be hybrids of those presented here. One of these is the required revenue method that computes a measure of the before-tax revenue in present or annual-value dollars required to cover the costs on an after-tax basis of an energy system (Ruegg and Short 1988:2223). Mathematical programming methods have been used to evaluate the optimal size or design of projects, as well as other mathematical and statistical techniques.

3.4 Risk Assessment

Many of the inputs to the above evaluation methods will be highly uncertain at the time an investment decision must be made. To make the most informed decision possible, an investor should employ these methods within a framework that explicitly accounts for risk and uncertainty.

Risk assessment provides decision makers with information about the "risk exposure" inherent in a given decision, i.e., the probability that the outcome will be different from the "best-guess" estimate. Risk assessment is also concerned with the *risk attitude* of the decision maker that describes his/her willingness to take a chance on an investment of uncertain outcome. Risk assessment techniques are typically used in conjunction with the evaluation methods outlined earlier; and not as stand-alone evaluation techniques.

The risk assessment techniques range from simple and partial to complex and comprehensive. Though none takes the risk out of making decisions, the techniques—if used correctly—can help the decision maker make more informed choices in the face of uncertainty.

This chapter provides an overview of the following probability-based risk assessment techniques:

- Expected value analysis
- Mean-variance criterion and coefficient of variation
- Risk-adjusted discount rate technique
- Certainty equivalent technique
- Monte Carlo simulation
- Decision analysis
- Real options
- Sensitivity analysis

There are other techniques that are used to assess risks and uncertainty (e.g., CAP_M, and break-even analysis), but those are not treated here.

3.4.1 Expected Value Analysis

Expected value (EV) analysis provides a simple way of taking into account uncertainty about input values, but it does not provide an explicit measure of risk in the outcome. It is helpful in explaining and illustrating risk attitudes.

3.4.1.1 How to Calculate EV

An *expected value* is the sum of the products of the dollar value of alternative outcomes and their probabilities of occurrence. That is, where a_i ($i=1,\ldots,n$) indicates the value associated with alternative outcomes of a decision, and p_i indicates the probability of occurrence of alternative a_i, the EV of the decision is calculated as follows:

$$\mathrm{EV} = a1p1 + a2p2 + \ldots + a_n p_n. \tag{3.7}$$

3.4.1.2 Example of EV Analysis

The following simplified example illustrates the combining of EV analysis and NPV analysis to support a purchase decision.

Assume that a not-for-profit organization must decide whether to buy a given piece of energy-saving equipment. Assume that the unit purchase price of the equipment is $100,000, the yearly operating cost is $5,000 (obtained by a fixed-price contract), and both costs are known with certainty. The annual energy cost savings, on the other hand, are uncertain, but can be estimated in probabilistic terms as shown in Table 3.1 in the columns headed a_1, p_1, a_2, and p_2. The present-value calculations are also given in Table 3.1.

If the equipment decision were based only on NPV, calculated with the "best-guess" energy savings (column a_1), the equipment purchase would be found to be uneconomic. But if the possibility of greater energy savings is taken into account by using the EV of savings rather than the best guess, the conclusion is that, over repeated applications, the equipment is expected to be cost effective. The expected NPV of the energy-saving equipment is $25,000 per unit.

3.4.1.3 Advantages and Disadvantages of the EV Technique

An advantage of the technique is that it predicts a value that tends to be closer to the actual value than a simple "best-guess" estimate over repeated instances of the same event, provided, of course, that the input probabilities can be estimated with some accuracy.

A disadvantage of the EV technique is that it expresses the outcome as a single-value measure, such that there is no explicit measure of risk. Another is that the estimated outcome is predicated on many replications of the event, with the EV, in effect, a weighted average of the outcome over many like events. But the EV is unlikely to occur for a single instance of an event. This is analogous to a single coin toss: the outcome will be either heads or tails, not the probabilistic-based weighted average of both.

TABLE 3.1 Expected Value Example

Year	Equipment Purchase ($1000)	Operating Costs ($1000)	Energy Savings					
			A_1 ($1000)	P_1	A_2 ($1000)	P_2	PV[a] Factor	PV ($1000)
0	−100	—	—	—	—	—	1	−100
1		−5	25	0.8	50	0.2	0.926	23
2		−5	30	0.8	60	0.2	0.857	27
3		−5	30	0.7	60	0.3	0.794	27
4		−5	30	0.6	60	0.4	0.7354	27
5		−5	30	0.8	60	0.2	0.681	21
Expected Net Present Value:								25

[a] Present value calculations are based on a discount rate of 8%. Probabilities sum to 1.0 in a given year.

3.4.1.4 Expected Value and Risk Attitude

Expected values are useful in explaining risk attitude. Risk attitude may be thought of as a decision maker's preference between taking a chance on an uncertain money payout of known probability versus accepting a sure money amount. Suppose, for example, a person were given a choice between accepting the outcome of a fair coin toss where heads means winning \$10,000, and tails means losing \$5,000 and accepting a certain cash amount of \$2,000. EV analysis can be used to evaluate and compare the choices. In this case, the EV of the coin toss is \$2,500, which is \$500 more than the certain money amount. The "risk-neutral" decision maker will prefer the coin toss because of its higher EV. The decision maker who prefers the \$2,000 certain amount is demonstrating a "risk-averse" attitude. On the other hand, if the certain amount were raised to \$3,000 and the first decision maker still preferred the coin toss, he or she would be demonstrating a "risk-taking" attitude. Such tradeoffs can be used to derive a "utility function" that represents a decision maker's risk attitude.

The risk attitude of a given decision maker is typically a function of the amount at risk. Many people who are risk averse when faced with the possibility of significant loss become risk neutral—or even risk taking—when potential losses are small. Because decision makers vary substantially in their risk attitudes, there is a need to assess not only risk exposure (i.e., the degree of risk inherent in the decision) but also the risk attitude of the decision maker.

3.4.2 Mean-Variance Criterion and Coefficient of Variation

These techniques can be useful in choosing among risky alternatives, if the mean outcomes and standard deviations (variation from the mean) can be calculated.

Consider a choice between two projects—one with higher mean NB and a lower standard deviation than the other. This situation is illustrated in Figure 3.4. In this case, the project whose probability distribution is labeled B can be said to have stochastic dominance over the project labeled A. Project B is preferable to project A, both on grounds that its output is likely to be higher and that it entails less risk of loss. But what if project A, the alternative with higher risk, has the higher mean NB, as illustrated in Figure 3.5? If this were the case, the mean-variance criterion (MVC) would provide inconclusive results.

When there is not stochastic dominance of one project over the other(s), it is helpful to compute the coefficient of variation (CV) to determine the relative risk of the alternative projects. The CV indicates which alternative has the lower risk per unit of project output. Risk-averse decision makers will prefer the alternative with the lower CV, other things being equal. The CV is calculated as follows:

$$\mathrm{CV} = \sigma/\mu, \tag{3.8}$$

where CV is the coefficient of variation, σ is the standard deviation, and μ is the mean.

The principal advantage of these techniques is that they provide quick, easy-to-calculate indications of the returns and risk exposure of one project relative to another. The principal disadvantage is that the

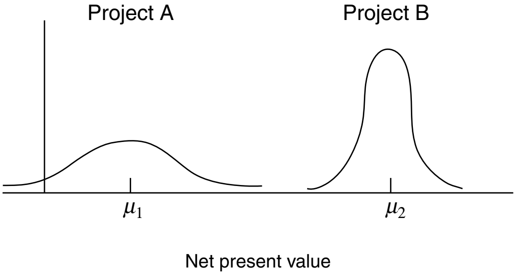


FIGURE 3.4 Stochastic dominance as demonstrated by mean-variance criterion.

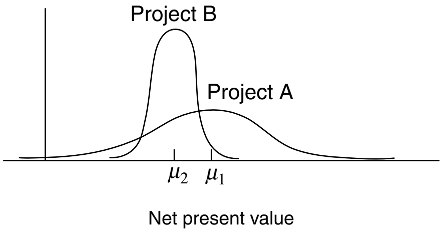


FIGURE 3.5 Inconclusive results from mean-variance criterion.

MVC does not provide a clear indication of preference when the alternative with the higher mean output has the higher risk, or vice versa.

3.4.3 Risk-Adjusted Discount Rate Technique

The risk-adjusted discount rate (RADR) technique takes account of risk through the discount rate. If a project's benefit stream is riskier than that of the average project in the decision maker's portfolio, a higher than normal discount rate is used; if the benefit stream is less risky, a lower than normal discount rate is used. If costs are the source of the higher-than-average uncertainty, a lower than normal discount rate is used and vice versa. The greater the variability in benefits or costs, the greater the adjustment in the discount rate.

The RADR is calculated as follows:

$$\mathrm{RADR} = \mathrm{RFR} + \mathrm{NRA} + \mathrm{XRA}, \tag{3.9}$$

where RADR is the risk-adjusted discounted rate, RFR is the risk-free discount rate, generally set equal to the treasury bill rate, NRA is the "normal" risk adjustment to account for the average level of risk encountered in the decision maker's operations, and XRA is the extra risk adjustment to account for risk greater or less than normal risk.

An example of using the RADR technique is the following: A company is considering an investment in a new type of alternative energy system with high payoff potential and high risk on the benefits side. The projected cost and revenue streams and the discounted present values are shown in Table 3.2. The treasury bill rate, taken as the risk-free rate, is 8%. The company uses a normal risk adjustment of 4% to account for the average level of risk encountered in its operations. The revenues associated with this investment are judged to be more than twice as risky as the company's average investment, so an additional risk adjustment of 6% is added to the RADR. Hence, the RADR is 18%. With this RADR, the NPV of the investment is estimated to be a loss of $28 million. On the basis of this uncertainty analysis, the company would be advised to not accept the project.

Advantages of the RADR technique are that it provides a way to account for both risk exposure and risk attitude. Moreover, RADR does not require any additional steps for calculating NPV once a value of the RADR is established. The disadvantage is that it provides only an approximate adjustment. The value of the RADR is typically a rough estimate based on sorting investments into risk categories and adding a

TABLE 3.2 Risk-Adjusted Discount Rate Example

Year	Costs ($M)	Revenue ($M)	PV Costs[a] ($M)	PV Revenue[b] ($M)	NPV ($M)
0	80	—	80	—	−80
1	5	20	4	17	13
2	5	20	4	14	10
3	5	20	4	12	8
4	5	20	3	10	7
5	5	20	3	9	6
6	5	20	3	7	4
7	5	20	2	6	4
Total NPV					−28

[a] Costs are discounted with a discount rate of 12%.

[b] Revenues are discounted with the RADR discount rate of 18%.

"fudge factor" to account for the decision maker's risk attitude. It generally is not a fine-tuned measure of the inherent risk associated with variation in cash flows. Further, it typically is biased toward investments with short payoffs because it applies a constant RADR over the entire analysis period, even though risk may vary over time.

3.4.4 Certainty Equivalent Technique

The certainty equivalent (CE) technique adjusts investment cash flows by a factor that will convert the measure of economic worth to a "certainty equivalent" amount—the amount a decision maker will find equally acceptable to a given investment with an uncertain outcome. Central to the technique is the derivation of the certainty equivalent factor (CEF) that is used to adjust net cash flows for uncertainty.

Risk exposure can be built into the CEF by establishing categories of risky investments for the decision maker's organization and linking the CEF to the CV of the returns—greater variation translating into smaller CEF values. The procedure is as follows:

1. Divide the organization's portfolio of projects into risk categories. Examples of investment risk categories for a private utility company might be the following: low-risk investments: expansion of existing energy systems and equipment replacement; moderate-risk investments: adoption of new, conventional energy systems; and high-risk investments: investment in new alternative energy systems.
2. Estimate the coefficients of variation (see the section on the CV technique) for each investment-risk category (e.g., on the basis of historical risk-return data).
3. Assign CEFs by year, according to the coefficients of variation, with the highest-risk projects being given the lowest CEFs. If the objectives are to reflect only risk exposure, set the CEFs such that a risk-neutral decision maker will be indifferent between receiving the estimated certain amount and the uncertain investment. If the objective is to reflect risk attitude as well as risk exposure, set the CEFs such that the decision maker with his or her own risk preference will be indifferent.

To apply the technique, proceed with the following steps:

4. Select the measure of economic performance to be used, such as the measure of NPV (i.e., NB).
5. Estimate the net cash flows and decide in which investment-risk category the project in question fits.
6. Multiply the yearly net cash flow amounts by the appropriate CEFs.
7. Discount the adjusted yearly net cash flow amounts with a risk-free discount rate (a risk-free discount rate is used because the risk adjustment is accomplished by the CEFs).
8. Proceed with the remainder of the analysis in the conventional way.

In summary, the certainty equivalent NPV is calculated as follows:

$$\mathrm{NPV_{CE}} = \sum_{t=0}^{N} [(\mathrm{CEF}_t(B_t - C_t))/(1 + \mathrm{RFD})^t], \tag{3.10}$$

where $\mathrm{NPV_{CE}}$ is the NPV adjusted for uncertainty by the CE technique, B_t is the estimated benefits in time period t, C_t is the estimated costs in time period t, and RFD is the risk-free discount rate.

Table 3.3 illustrates the use of this technique for adjusting net present-value calculations for an investment in a new, high-risk alternative energy system. The CEF is set at 0.76 and is assumed to be constant with respect to time.

A principal advantage of the CE Technique is that it can be used to account for both risk exposure and risk attitude. Another is that it separates the adjustment of risk from discounting and makes it possible to make more precise risk adjustments over time. A major disadvantage is that the estimation of CEF is only approximate.

TABLE 3.3 Certainty Equivalent (CE)

Yearly Net Cash Flow ($M)		CV	CEF	RFD Discount Factors[a]	NPV ($M)
1	−100	0.22	0.76	0.94	−71
2	−100	0.22	0.76	0.89	−68
3	20	0.22	0.76	0.84	13
4	30	0.22	0.76	0.79	18
5	45	0.22	0.76	0.75	26
6	65	0.22	0.76	0.7	35
7	65	0.22	0.76	0.67	33
8	65	0.22	0.76	0.63	31
9	50	0.22	0.76	0.59	22
10	50	0.22	0.76	0.56	21
Total NPV					

[a] The RFD is assumed equal to 6%.

3.4.5 Monte Carlo Simulation

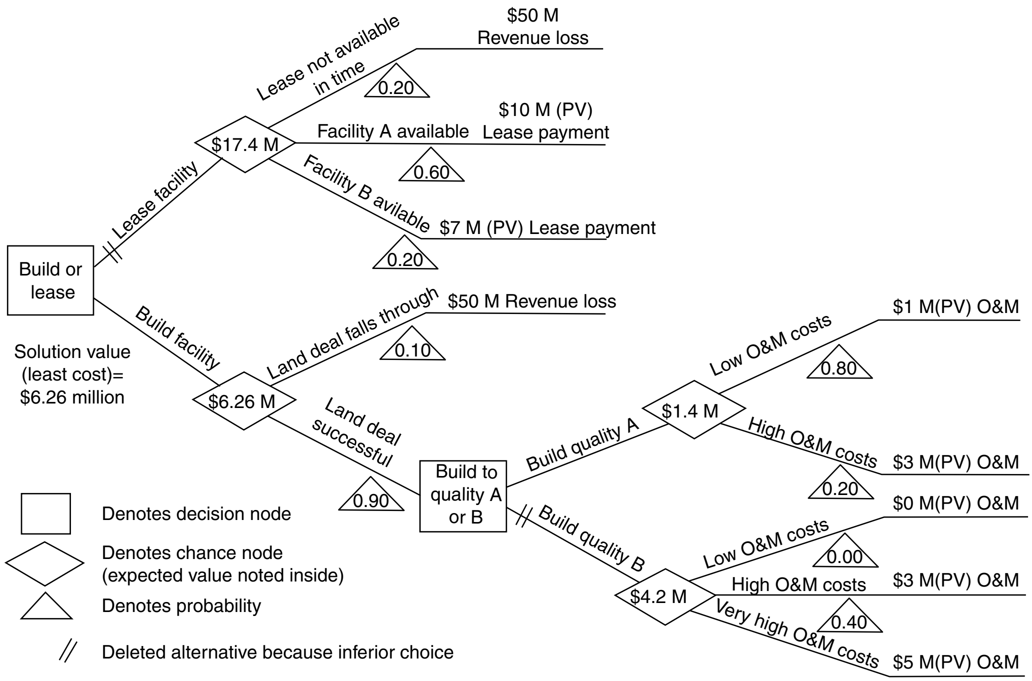
A Monte Carlo simulation entails the iterative calculation of the measure of economic worth from probability functions of the input variables. The results are expressed as a probability density function and as a cumulative distribution function. The technique thereby enables explicit measures of risk exposure to be calculated. One of the economic-evaluation methods treated earlier is used to calculate economic worth; a computer is employed to sample repeatedly—hundreds of times—from the probability distributions and make the calculations. A Monte Carlo simulation can be performed by the following steps:

1. Express variable inputs as probability functions. Where there are interdependencies among input values, multiple probability density functions, tied to one another, may be needed.
2. For each input for which there is a probability function, draw randomly an input value; for each input for which there is only a single value; take that value for calculations.
3. Use the input values to calculate the economic measure of worth and record the results.
4. If inputs are interdependent, such that input X is a function of input Y, first draw the value of Y, then draw randomly from the X values that correspond to the value of Y.
5. Repeat the process many times until the number of results is sufficient to construct a probability density function and a cumulative distribution function.
6. Construct the probability density function and cumulative distribution function for the economic measure of worth, and perform statistical analysis of the variability.

The strong advantage of the technique is that it expresses the results in probabilistic terms, thereby providing explicit assessment of risk exposure. A disadvantage is that it does not explicitly treat risk attitude; however, by providing a clear measure of risk exposure, it facilitates the implicit incorporation of risk attitude in the decision. The necessity of expressing inputs in probabilistic terms and the extensive calculations are also often considered disadvantages.

3.4.6 Decision Analysis

Decision analysis is a versatile technique that enables both risk exposure and risk attitude to be taken into account in the economic assessment. It diagrams possible choices, costs, benefits, and probabilities for a given decision problem in "decision trees," which are useful in understanding the possible choices and outcomes.



Faced with a decision to lease or build a facility, the least-cost choice is to build the facility, with an expected cost of $6.26 million based on the above costs and probabilities of outcomes.

FIGURE 3.6 Decision tree: build versus lease.

Although it is not possible to capture the richness of this technique in a brief overview, a simple decision tree, shown in Figure 3.6, is discussed to give a sense of how the technique is used. The decision problem is whether to lease or build a facility. The decision must be made now, based on uncertain data. The decision tree helps to structure and analyze the problem. The tree is constructed left to right and analyzed right to left. The tree starts with a box representing a decision juncture or node—in this case, whether to lease or build a facility. The line segments branching from the box represent the two alternative paths: the upper one the lease decision and the lower one the build decision. Each has a cost associated with it that is based on the expected cost to be incurred along the path. In this example, the minimum expected cost of $6.26 M is associated with the option to build a facility.

An advantage of this technique is that it helps to understand the problem and to compare alternative solutions. Another advantage is that, in addition to treating risk exposure, it can also accommodate risk attitude by converting benefits and costs to utility values (not addressed here). A disadvantage is that the technique, as typically applied, does not provide an explicit measure of the variability of the outcome.

3.4.7 Real Options Analysis

Real options analysis (ROA) is an adaptation of financial options valuation techniques[4] to real asset investment decisions. ROA is a method used to analyze decisions in which the decision maker has one or more options regarding the timing or sequencing of an investment. It explicitly assumes that the investment is partially or completely irreversible, that there exists leeway or flexibility about the timing of

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[4] Financial options valuation is credited to Fisher Black and Myron Scholes who demonstrated mathematically that the value of a European call option—an option, but not the obligation, to purchase a financial asset for a given price (i.e., the exercise or strike price) on a particular date (i.e., the expiry date) in the future—depends on the current price of the stock, the volatility of the stock's price, the expiry date, the exercise price, and the risk-free interest rate (see Black and Scholes 1973).

the investment, and that it is subject to uncertainty over future payoffs. Real options can involve options (and combinations) to defer, sequence, contract, shut down temporarily, switch uses, abandon, or expand the investment. This is in contrast to the NPV method that implies the decision is a "now or never" choice.

The value of an investment with an option is said to equal the value of the investment using the traditional NPV method (that implicitly assumes no flexibility or option) plus the value of the option. The analysis begins by construction of a decision tree with the option decision embedded in it. There are two basic methods to solve for the option value: the risk-adjusted replicating portfolio (RARP) approach and the risk-neutral probability (RNP) approach. The RARP discounts the expected project cash flows at a risk-adjusted discounted rate, whereas the RNP approach discounts certainty-equivalent cash flows at a risk-free rate. In other words, the RARP approach takes the cash flows essentially as-is and adjusts the discount rate per time period to reflect that fact that the risk changes as one moves through the decision tree (e.g., risk declines with time as more information becomes available). In the RNP approach, the cash flows themselves essentially are adjusted for risk and discounted at a risk-free rate.

Copeland and Antikarov provide an overall four-step approach for ROA:[5]

1. Step 1: Compute a base-case traditional NPV (e.g., without flexibility).
2. Step 2: Model the uncertainty using (binominal) event trees (still without flexibility; e.g., without options)—although uncertainty is incorporated, the "expected" value of Step 2 should equal that calculated in Step 1.
3. Step 3: Create a decision tree incorporating decision nodes for options, as well as other (nondecision and nonoption decisions) nodes.
4. Step 4: Conduct a ROA by valuing the payoffs, working backward in time, node by node, using the RARP or RNP approaches to calculate the ROA value of the investment.

3.4.8 Sensitivity Analysis

Sensitivity analysis is a technique for taking into account uncertainty that does not require estimates of probabilities. It tests the sensitivity of economic performance to alternative values of key factors about which there is uncertainty. Although sensitivity analysis does not provide a single answer in economic terms, it does show decision makers how the economic viability of a renewable energy or efficiency project changes as fuel prices, discount rates, time horizons, and other critical factors vary.

Figure 3.7 illustrates the sensitivity of fuel savings realized by a solar energy-heating system to three critical factors: time horizons (zero to 25 years), discount rates (D equals 0%, 5%, 10%, and 15%), and energy escalation rates (E equals 0%, 5%, 10%, and 15%). The present value of savings is based on yearly fuel savings valued initially at $1,000.

Note that, other things being equal, the present value of savings increase with time—but less with higher discount rates and more with higher escalation rates. The huge impact of fuel price escalation is most apparent when comparing the top line of the graph ($D=0.10$, $E=0.15$) with the line next to the bottom ($D=0.10$, $E=0$). The present value of savings at the end of 25 years is approximately $50,000 with a fuel escalation rate of 15%, and only about $8,000 with no escalation, other things equal. Whereas the quantity of energy saved is the same, the dollar value varies widely, depending on the escalation rate.

This example graphically illustrates a situation frequently encountered in the economic justification of energy efficiency and renewable energy projects: the major savings in energy costs, and thus the bulk of the benefits, accrue in the later years of the project and are highly sensitive to both the assumed rate of fuel-cost escalation and the discount rate. If the two rates are set equal, they will be offsetting as shown by the straight line labeled $D=0$, $E=0$ and $D=0.10$, $E=0.10$.

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[5] See Dixit Avinash and Pindyck (1994), which is considered the "bible" of real options, and Copeland Antikarov (2001), which offers more practical spreadsheet methods.

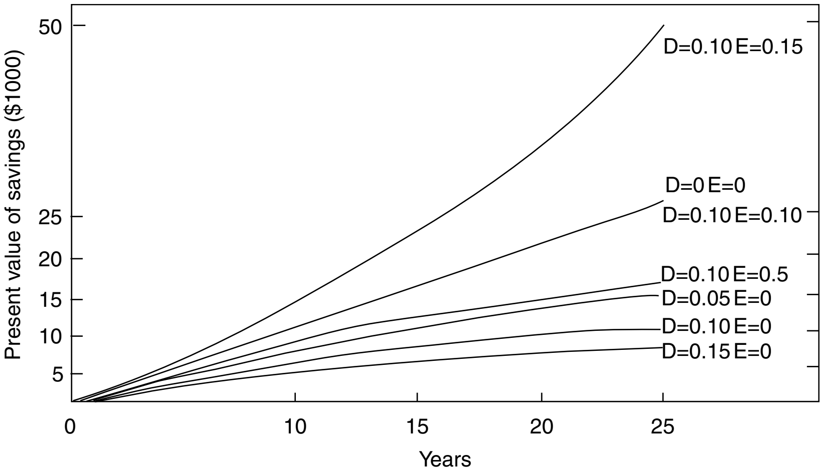


FIGURE 3.7 Sensitivity of present value energy savings to time horizons, discount rates, and energy price escalation rates.

3.5 Building Blocks of Evaluation

Beyond the formula for the basic evaluation methods and risk assessment techniques, the practitioner needs to know some of the "nuts-and-bolts" of carrying out an economic analysis. He or she needs to know how to structure the evaluation process; how to choose a method of evaluation; how to estimate dollar costs and benefits; how to perform discounting operations; how to select an analysis period; how to choose a discount rate; how to adjust for inflation; how to take into account taxes and financing; how to treat residual values; and how to reflect assumptions and constraints, among other things. This section provides brief guidelines for these topics.

3.5.1 Structuring the Evaluation Process and Selecting a Method of Evaluation

A good starting point for the evaluation process is to define the problem and the objective. Identify any constraints to the solution and possible alternatives. Consider if the best solution is obvious, or if economic analysis and risk assessment are needed to help make the decision. Select an appropriate method of evaluation and a risk assessment technique. Compile the necessary data and determine what assumptions are to be made. Apply the appropriate formula(s) to compute a measure of economic performance under risk. Compare alternatives and make the decision, taking into account any incommensurable effects that are not included in the dollar benefits and costs. Take into account the risk attitude of the decision maker, if it is relevant.

Although the six evaluation methods given earlier are similar, they are also sufficiently different in that they are not always equally suitable for evaluating all types of energy investment decisions. For some types of decisions, the choice of method is more critical than for others. Figure 3.8 categorizes different investment types and the most suitable evaluation methods for each. If only a single investment is being considered, the "accept–reject" decision can often be made by any one of several techniques, provided the correct criterion is used.

The accept/reject criteria are as follows:

- LCC technique: LCC must be lower as a result of the energy efficiency or renewable energy investment than without it.
- NPV (NB) technique: NPV must be positive as a result of the investment.

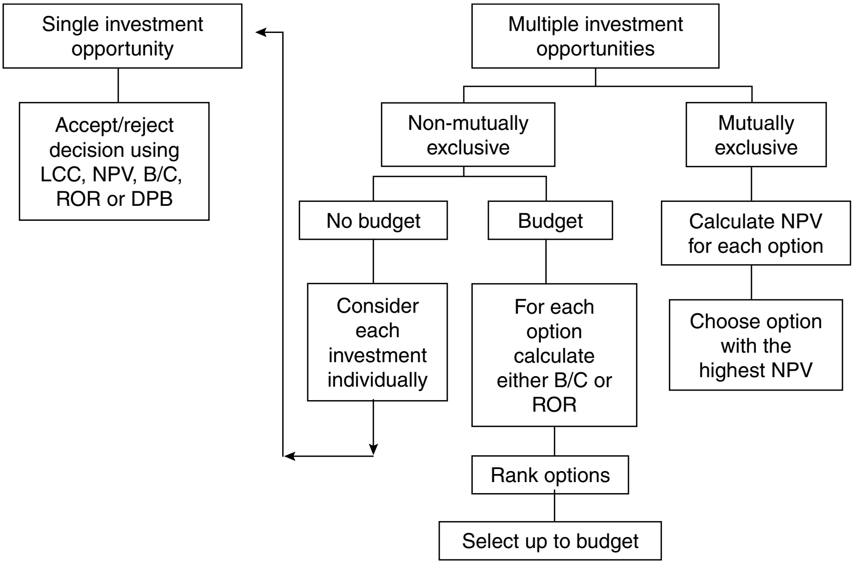


FIGURE 3.8 Investment decisions and evaluation methods.

- B/C (SIR) technique: B/C (SIR) must be greater than one.
- IRR technique: the IRR must be greater than the investor's minimum acceptable rate of return.
- DPB technique: the number of years to achieve DPB must be less than the project life or the investor's time horizon, and there are no cash flows after payback is achieved that would reverse payback.

If multiple investment opportunities are available, but only one investment can be made (i.e., they are mutually exclusive), any of the methods (except DPB) will usually work, provided they are used correctly. However, the NPV method is usually recommended for this purpose, because it is less likely to be misapplied. The NPV of each investment is calculated and the investment with the highest present value is the most economic. This is true even if the investments require significantly different initial investments, have significantly different times at which the returns occur, or have different useful lifetimes. Examples of mutually exclusive investments include different system sizes (e.g., three different photovoltaic array sizes are being considered for a single rooftop), different system configurations (e.g., different turbines are being considered for the same wind farm), and so forth.

If the investments are not mutually exclusive, then (as shown in Figure 3.8), one must consider whether there is an overall budget limitation that would restrict the number of economic investments that might be undertaken. If there is no budget (i.e., no limitation on the investment funds available), than there is really no comparison to be performed and the investor simply makes an accept–reject decision for each investment individually as described above.

If funds are not available to undertake all of the investments (i.e., there is a budget), then the easiest approach is to rank the alternatives, with the best having the highest BCR or rate of return. (The investment with the highest NPV will not necessarily be the one with the highest rank, because present value does not show return per unit investment). Once ranked, those investments at the top of the priority list are selected until the budget is exhausted.

In the case where a fast turnaround on investment funds is required, DPB is recommended. The other methods, although more comprehensive and accurate for measuring an investment's lifetime profitability, do not indicate the time required for recouping the investment funds.

3.5.2 Discounting

Some or all investment costs in energy efficiency or renewable energy systems are incurred near the beginning of the project and are treated as "first costs." The benefits, on the other hand, typically accrue over the life span of the project in the form of yearly energy saved or produced. To compare benefits and costs that accrue at different points in time, it is necessary to put all cash flows on a time-equivalent basis. The method for converting cash flows to a time-equivalent basis is often called *discounting*.

The value of money is time-dependent for two reasons: First, inflation or deflation can change the buying power of the dollar. Second, money can be invested over time to yield a return over and above inflation. For these two reasons, a given dollar amount today will be worth more than that same dollar amount a year later. For example, suppose a person were able to earn a maximum of 10% interest per annum risk-free. He or she would require $1.10 a year from now to be willing to forego having $1 today. If the person were indifferent between $1 today and $1.10 a year from now, then the 10% rate of interest would indicate that person's time preference for money. The higher the time preference, the higher the rate of interest required to make future cash flows equal to a given value today. The rate of interest for which an investor feels adequately compensated for trading money now for money in the future is the appropriate rate to use for converting present sums to future equivalent sums and future sums to present equivalent sums (i.e., the rate for discounting cash flows for that particular investor). This rate is often called the *discount rate*.

To evaluate correctly the economic efficiency of an energy efficiency or renewable energy investment, it is necessary to convert the various expenditures and savings that accrue over time to a lump-sum, time-equivalent value in some base year (usually the present), or to annual values. The remainder of this section illustrates how to discount various types of cash flows.

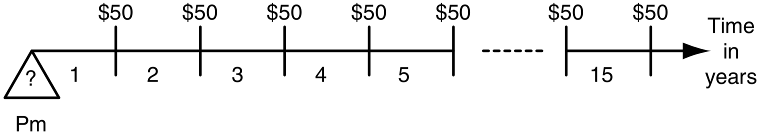
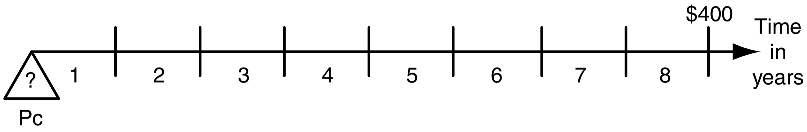
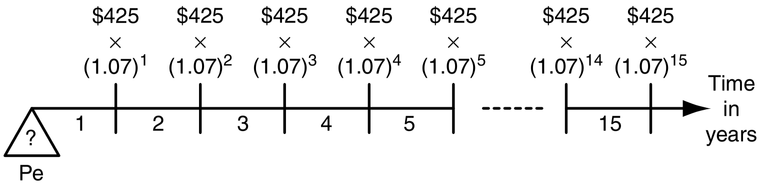
Discounting is illustrated by Figure 3.9 in a problem of installing, maintaining, and operating a heat pump, as compared to an alternative heating/cooling system. The LCC calculations are shown for two reference times. The first is the present, and it is therefore called a *present value*. The second is based on a yearly time scale and is called an *annual value*. These two reference points are the most common in economic-evaluations of investments. When the evaluation methods are derived properly, each time basis will give the same relative ranking of investment priorities.

The assumptions for the heat pump problem—which are given only for the sake of illustration and not to suggest actual prices—are as follows:

1. The residential heat pump (not including the ducting) costs $1,500 to purchase and install.
2. The heat pump has a useful life of 15 years.
3. The system has annual maintenance costs of $50 every year during its useful life, fixed by contractual agreement.
4. A compressor replacement is required in the eighth year at a cost of $400.
5. The yearly electricity cost for heating and cooling is $425, evaluated at the outset, and increased at a rate of 7% per annum due to rising electricity prices.
6. The discount rate (a nominal rate that includes an inflation adjustment) is 10%.
7. No salvage value is expected at the end of 15 years.

The LCCs in the sample problem are derived only for the heat pump and not for alternative heating/cooling systems. Hence, no attempt is made to compare alternative systems in this discounting example. To do so would require similar calculations of LCCs for other types of heating/cooling systems. Total costs of a heat pump system include costs of purchase and installation, maintenance, replacements, and electricity for operation. Using the present as the base-time reference point, one needs to convert each of these costs to the present before summing them. Assuming that the purchase and installation costs occur at the base reference point (the present), the $1,500 is already in present value terms.

Figure 3.9 illustrates how to convert the other cash flows to present values. The first task is to convert the stream of annual maintenance costs to present value. The maintenance costs, as shown in the cash flow diagram of Figure 3.9, are $50 per year, measured in current dollars (i.e., dollars of the years in which

Task description[a]	Cash flow diagram	Discounting operation[b]
(Find P, given A) Find the present value (Pm) of the $50 annual maintenance cost (Am) over 15 yr		Pm = Am + UPW Pm = $50 (UPW, 10%, 15 yr) Pm = $50 (7.606) = $380
(Find P, given F) Find the present value (Pc) of the $400 future cost of replacing compressor (Fc) at end of 8 yr		Pm = Fc + SPW Pm = $400 (SPW, 10%, 8 yr) Pm = $400 (0.4665) = $187
(Find P, given A with escalation) Find the present value (Pc) of the annual electricity costs (Ae) over 15 yr, beginning with a first year's cost of $425 and electricity cost escalation of 7%/yr		Pe = Ae + UPW$^+$ Pe = $425 (UPW$^+$, 10%, 15 yr 7% escalation) Pe = $425 (12.1092) = $5,146
Find the total present value of the heat pump (Ph)		Ph = purchase and installation cost + Pm + Pc + Pe Ph = $1,500 + $380 + $187 + $5,146 Ph = $7,213

Note: [a] P Present value, A = Annual value, F = Future value.

[b] UPW = Uniform present worth factor, SPW = Single present worth factor, UPW$^+$= Uniform present worth factor with energy escalation.

Purchase and installation costs are $1,500 incurred initially.

FIGURE 3.9 Discounting for present value: a heat pump example. (From Marshall, H. E. and Ruegg, R. T., in *Simplified Energy Design Economics*, F. Wilson, ed., National Bureau of Standards, Washington, DC, 1980.)

TABLE 3.4 Discount Formulas

Standard Nomenclature	Use When	Standard Notation	Algebraic Form
Single compound amount	Given *P*; to find *F*	(SCA, *d*%, *N*)	$F=P(1+d)^N$
Single present worth	Given *F*; to find *P*	(SPW, *d*%, *N*)	$P=F\frac{1}{(1+d)^N}$
Uniform compound amount	Given *A*; to find *F*	(UCA, *d*%, *N*)	$F=A\frac{(1+d)^N-1}{d}$
Uniform sinking fund	Given *F*; to find *A*	(USF, *d* %, *N*)	$A=F\frac{d}{(1+d)^N-1}$
Uniform capital recovery	Given *P*; to find *A*	(UCR, *d*%, *N*)	$A=P\frac{d(1+d)^N}{(1+d)^N-1}$
Uniform present worth	Given *A*; to find *P*	(UPW, *d*%, *N*)	$P=A\frac{(1+d)^N-1}{d(1+d)^N}$
Uniform present worth modified	Given *A* escalating at a rate e; to find *P*	(UPW*, *d*%, *e*, *N*)	$P=A\frac{(1+e)\left[1-\left(\frac{1+e}{1+d}\right)^N\right]}{(d-e)}$

P, a present sum of money; *F*, a future sum of money, equivalent to *P* at the end of *N* periods of time at a discount rate of *d*; *N*, number of interest periods; *A*, an end-of-period payment (or receipt) in a uniform series of payments (or receipts) over *N* periods at *discount rate d*, usually annually; *e*, a rate of escalation in *A* in each of *N* periods.

they occur). The triangle indicates the value to be found. The practice of compounding interest at the end of each year is followed here. The present refers to the beginning of year one.

The discounting operation for calculating the present value of maintenance costs (last column of Figure 3.9) is to multiply the annual maintenance costs times the uniform present worth (UPW) factor. The UPW is a multiplicative factor computed from the formula given in Table 3.4, or taken from a look-up table of factors that have been published in many economics textbooks. UPW factors make it easy to calculate the present values of a uniform series of annual values. For a discount rate of 10% and a time period of 15 years, the UPW factor is 7.606. Multiplying this factor by $50 gives a present value maintenance cost equal to $380. Note that the $380 present value of $50 per year incurred in each of 15 years is much less than simply adding $50 for 15 years (i.e., $750). Discounting is required to achieve correct statements of costs and benefits over time.

The second step is to convert the one-time future cost of compressor replacement, $400, to its present value. The operation for calculating the present value of compressor replacement is to multiply the future value of the compressor replacement times the single-payment present worth factor (SPW) that can be calculated from the formula in Table 3.4, or taken from a discount factor look-up table. For a discount rate of 10% and a time period of 15 years, the SPW factor is 0.4665. Multiplying this factor by $400 gives a present-value cost of the compressor replacement of $187, as shown in the last column of Figure 3.9. Again, note that discounting makes a significant difference in the measure of costs. Failing to discount the $400 would result in an overestimate of cost in this case of $213.

The third step is to convert the annual electricity costs for heating and cooling to present value. A year's electricity costs, evaluated at the time of installation of the heat pump, are assumed to be $425. Electricity prices, for purposes of illustration, are assumed to increase at a rate of 7% per annum. This is reflected in Table 3.4 by multiplying $425 times $(1.07)^t$ where $t=1,2,\ldots,15$. The electricity cost at the end of the fourth year, for example, is $\$425(1.07)^4=\$557$.

The discounting operation for finding the present value of all electricity costs (shown in Figure 3.9) is to multiply the initial, yearly electricity costs times the appropriate UPW* factor. (An asterisk following UPW denotes that a term for price escalation is included.) The UPW or UPW* discount formulas in Table 3.4 can also be used to obtain present values from annual costs or multiplicative discount factors from look-up tables can be used. For a period of 15 years, a discount rate of 10%, and an escalation rate of 7%, the UPW* factor is 12.1092. Multiplying the factor by $425 gives a present value of electricity costs of $5,146. Note, once again, that failing to discount (i.e., simply adding annual electricity expenses in current prices) would overestimate costs by $1,229 ($6,376 − $5,146). Discounting with a UPW factor that does not incorporate energy price escalation would underestimate costs by $1,913 ($5,146 − $3,233).

The final operation described in Figure 3.9 is to sum purchase and installation cost and the present values of maintenance, compressor replacement, and electricity costs. Total LCCs of the heat pump in present value terms are $7,213. This is one of the amounts that a designer would need for comparing the cost-effectiveness of heat pumps to alternative heating/cooling systems.

Only one discounting operation is required for converting the present- value costs of the heat pump to annual value terms. The total present-value amount is converted to the total annual value simply by multiplying it by the uniform capital recovery factor (UCR)—in this case the UCR for 10% and 15 years. The UCR factor, calculated with the UCR formula found in Table 3.4, is 0.13147. Multiplying this factor by the total present value of $7,213 gives the cost of the heat pump as $948 in annual value terms. The two figures—$7,213 and $948 per year—are time-equivalent values, made consistent through the discounting.

Figure 3.9 provides a model for the designer who must calculate present values from all kinds of benefit or cost streams. Most distributions of values occurring in future years can be handled with the SPW, the UPW, or the UPW* factors.

3.5.3 Discount Rate

Of the various factors affecting the NB of energy efficiency and renewable energy investments, the discount rate is one of the most dramatic. A project that appears economic at one discount rate will often appear uneconomic at another rate. For example, a project that yields net savings at a 6% discount rate might yield net losses if evaluated with a 7% rate.

As the discount rate is increased, the present value of any future stream of costs or benefits is going to become smaller. High discount rates tend to favor projects with quick payoffs over projects with benefits deferred further in the future.

The discount rate should be set equal to the rate of return available on the next-best investment opportunity of similar risk to the project in question, i.e., it should indicate the opportunity cost of the investor.

The discount rate may be formulated as a “real rate” exclusive of general price inflation or as a “nominal rate” inclusive of inflation. The former should be used to discount cash flows that are stated in constant dollars. The latter should be used to discount cash flows stated in current dollars.

3.5.4 Inflation

Inflation is a rise in the general price level. Because future price changes are unknown, it is frequently assumed that prices will increase at the rate of inflation. Under this assumption, it is generally easier to conduct all economic-evaluations in constant dollars and to discount those values using “real” discount rates. For example, converting the constant dollar annual maintenance costs in Figure 3.9 to a present value can be easily done by multiplying by a uniform present-worth factor because the maintenance costs do not change over time. However some cash flows are more easily expressed in current dollars, e.g., equal loan payments, tax depreciation. These can be converted to present values using a nominal discount rate.

3.5.5 Analysis Period

The analysis period is the length of time over which costs and benefits are considered in an economic-evaluation. The analysis period need not be the same as either the “useful life” or the “economic life,” two common concepts of investment life. The useful life is the period over which the investment has some value; i.e., the investment continues to conserve or provide energy during this period. Economic life is the period during which the investment in question is the least-cost way of meeting the requirement. Often economic life is shorter than useful life.

The selection of an analysis period will depend on the objectives and perspective of the decision maker. A speculative investor who plans to develop a project for immediate sale, for example, may view the relevant time horizon as that short period of ownership from planning and acquisition of property to the first sale of the project. Although the useful life of a solar domestic hot water heating system, for example, might be 20 years, a speculative home builder might operate on the basis of a two-year time horizon, if the property is expected to change hands within that period. Only if the speculator expects to gain the benefit of those energy savings through a higher selling price for the building will the higher first cost of the solar energy investment likely be economic.

If an analyst is performing an economic analysis for a particular client, that client's time horizon should serve as the analysis period. If an analyst is performing an analysis in support of public investment or a policy decision, the life of the system or building is typically the appropriate analysis period.

When considering multiple investment options, it is best with some evaluation methods (such as LCC, IRR, and ORR) to use the same analysis period. With others like NPV and BCR, different analysis periods can be used. If an investment's useful life is shorter than the analysis period, it may be necessary to consider reinvesting in that option at the end its useful life. If an investment's useful life is longer than the analysis period, a salvage value may need to be estimated.

3.5.6 Taxes and Subsidies

Taxes and subsidies should be taken into account in economic-evaluations because they may affect the economic viability of an investment, the return to the investor, and the optimal size of the investment. Taxes, which may have positive and negative effects, include—but are not limited to—income taxes, sales taxes, property taxes, excise takes, capital gain taxes, depreciation recapture taxes, tax deductions, and tax credits.

Subsidies are inducements for a particular type of behavior or action. They include grants—cash subsidies of specified amounts; government cost sharing; loan-interest reductions, and tax-related subsidies. Income tax credits for efficiency or renewable energy expenditures provide a subsidy by allowing specific deductions from the investor's tax liability. Property tax exemptions eliminate the property taxes that would otherwise add to annual costs. Income tax deductions for energy efficiency or renewable energy expenses reduce annual tax costs. The imposition of higher taxes on nonrenewable energy sources raises their prices and encourages efficiency and renewable energy investments.

It is important to distinguish between a before-tax cash flow and an after-tax cash flow. For example, fuel costs are a before-tax cash flow (they can be expensed), whereas a production tax credit for electricity from wind is an after-tax cash flow.

3.5.7 Financing

Financing of an energy investment can alter the economic viability of that investment. This is especially true for energy efficiency and renewable energy investments that generally have large initial investment costs with returns spread out over time. Ignoring financing costs when comparing these investments against conventional sources of energy can bias the evaluation against the energy efficiency and renewable energy investments.

Financing is generally described in terms of the amount financed, the loan period, and the interest rate. Unless specified otherwise, a uniform payment schedule is usually assumed. Generally, financing improves the economic effectiveness of an investment if the after-tax nominal interest rate is less than the investor's nominal discount rate.

Financing essentially reduces the initial outlay in favor of additional future outlays over time—usually equal payments for a fixed number of years. These cash flows can be treated like any other: The equity portion of the capital cost occurs at the start of the first year, and the loan payments occur monthly or annually. The only other major consideration is the tax deductibility of the interest portion of the loan payments.

3.5.8 Residual Values

Residual values may arise from salvage (net of disposal costs) at the end of the life of systems and components, from reuse values when the purpose is changed, and from remaining value when assets are sold prior to the end of their lives. The present value of residuals can generally be expected to decrease, other things equal, as (1) the discount rate rises, (2) the equipment or building deteriorates, and (3) the time horizon lengthens.

To estimate the residual value of energy efficiency or renewable energy systems and components, it is helpful to consider the amount that can be added to the selling price of a project or building because of those systems. It might be assumed that a building buyer will be willing to pay an additional amount equal to the capitalized value of energy savings over the remaining life of the efficiency or renewable investment. If the analysis period is the same as the useful life, there will be no residual value.

3.6 Summary

There are multiple methods of economic performance and multiple techniques of risk analysis that can be selected and combined to improve decisions in energy efficiency and renewable energy investments. Economic performance can be stated in a variety of ways, depending on the problem and preferences of the decision maker: as NPV, as LCCs, as the cost of energy, as a rate of return, as years to payback, or as a ratio. To reflect the reality that most decisions are made under conditions of uncertainty, risk assessment techniques can be used to reflect the risk exposure of the project and the risk attitude of the decision maker. Rather than expressing results in single, deterministic terms, they can be expressed in probabilistic terms, thereby revealing the likelihood that the outcome will differ from the best-guess answer. These methods and techniques can be used to decide whether or not to invest in a given energy efficiency or renewable energy system; to determine which system design or size is economically efficient; to find the combination of components and systems that are expected to be cost-effective; to estimate how long before a project will break even; and to decide which energy-related investments are likely to provide the highest rate of return to the investor. The methods support the goal of achieving economic efficiency—which may differ from technical efficiency.

Glossary

Analysis period: Length of time over which costs and benefits are considered in an economic-evaluation.

Benefit/cost (B/C) or saving-to-investment (SIR) ratio: A method of measuring the economic performance of alternatives by dividing present value benefits (savings) by present value costs.

Constant dollars: Values expressed in terms of the general purchasing power of the dollar in a base year. Constant dollars do not reflect price inflation or deflation.

Cost-effective investment: The least-cost alternative for achieving a given level of performance.

Current dollars: Values expressed in terms of actual prices of each year (i.e., current dollars reflect price inflation or deflation).

Discount rate: Based on the opportunity cost of capital, this minimum acceptable rate of return is used to convert benefits and costs occurring at different times to their equivalent values at a common time.

Discounted payback period: The time required for the discounted annual NB derived from an investment to pay back the initial investment.

Discounting: A technique for converting cash flows that occur over time to equivalent amounts at a common point in time using the opportunity cost for capital.

Economic efficiency optimization: Maximizing NB or minimizing costs for a given level of benefits (i.e., “getting the most for your money”).

Economic life: That period of time over which an investment is considered to be the least-cost alternative for meeting a particular objective.

Future value (worth): The value of a dollar amount at some point in the future, taking into account the opportunity cost of capital.

Internal rate of return: The discount rate that equates total discounted benefits with total discounted costs.

Investment costs: The sum of the planning, design, and construction costs necessary to obtain or develop an asset.

Levelized cost of energy: The before-tax revenue required per unit of energy to cover all costs plus a profit/return on investment equal to the discount rate used to levelize the costs.

Life-cycle cost: The present-value total of all relevant costs associated with an asset or project over the analysis period.

Net benefits: Benefits minus costs.

Present value (worth): Past, present, or future cash flows all expressed as a lump sum amount as of the present time, taking into account the time value of money.

Real options analysis: Method used to analyze investment decisions in which the decision maker has one or more options regarding the timing or sequencing of investment.

Risk assessment: As applied to economic decisions, the body of theory and practice that helps decision makers assess their risk exposures and risk attitudes to increase the probability that they will make economic choices that are best for them.

Risk attitude: The willingness of decision makers to take chances on investments with uncertain outcomes. Risk attitudes may be classified as *risk averse*, *risk neutral*, and *risk taking*.

Risk exposure: The probability that a project's economic outcome will be less favorable than what is considered economically desirable.

Sensitivity analysis: A non-probability-based technique for reflecting uncertainty that entails testing the outcome of an investment by altering one or more system parameters from the initially assumed values.

Time value of money: The amount that people are willing to pay for having money today rather than some time in the future.

Uncertainty: As used in the context of this chapter, a lack of knowledge about the values of inputs required for an economic analysis.

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4

Energy Audits for Buildings

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4.1 Introduction

This chapter describes energy audit procedures commonly used to improve the energy efficiency of residential and commercial buildings as well as industrial facilities. Moreover, the chapter summarizes proven energy-efficient technologies in the building sectors with some examples to highlight the cost-effectiveness of some of these technologies. A brief overview is also provided for currently available energy management programs where energy audit is crucial for their proper and successful implementation.

4.2 Background

To reduce the operating costs and the environmental impact associated with utilizing conventional energy resources, energy conservation and energy efficiency offer attractive solutions. Moreover, energy efficiency can avoid the need to build new power plants—that use conventional energy sources—at little cost and with no adverse environmental impact. In addition, energy efficiency and energy conservation have other beneficial impacts:

- Increases economic competitiveness. As stated by the International Energy Agency (IEA), investment in energy conservation provides a better return than investment in energy supply.

- Stretches the availability of limited nonrenewable energy resources and gains time for possible development of renewable and reliable energy resources such as solar energy.
- Decreases air and water pollution and thus improves health conditions.

Around the world, there is a vast potential for energy efficiency that has begun to be tapped in only a few countries. This potential exists for all energy end use sectors including buildings, industries, and transportation. One of the main challenges in this new millennium will be to increase the efficiency of production, distribution, and consumption of energy that will reduce costs and lower the environmental impacts. Therefore, energy efficiency can have beneficial impacts on economic competitiveness, the environment, and health.

In several industrialized countries, energy consumption has fluctuated in response to significant changes in oil prices, economic growth rates, and environmental concerns, especially since the oil crisis of the early 1970s. For instance, the U.S. energy consumption increased from 66 quadrillion British thermal units (Btu) in 1970–1994 quadrillion Btu in 1998 (EIA 1998). The energy costs in the U.S. economy represent about 8% of the gross domestic product (GDP), which is one of the highest among industrialized countries. One of the reasons for the high energy costs is that the U.S. consumes a significant fraction of the total world energy. Thus, the U.S. has the highest per capita energy-use rate in the world with an average of 350 million Btu per year, or the equivalent of 7 gallons of oil per person per day.

Figure 4.1 illustrates the rate of growth of the per capita energy-use and the population relative to 1973. It is interesting to note that the per capita energy-use rate remains almost constant—with relatively small fluctuations—since 1973 even though the population growth rate has clearly increased throughout the years. The higher oil prices in the 1970s (oil embargo in 1973 and the Iranian revolution in 1979) have mandated energy conservation and increased energy efficiency. The trend toward energy conservation, although relaxed during the 1980s, had continued in the 1990s due to the 1992 National Energy Policy Act (EPACT) which promotes more efficient use of energy in the U.S. In particular, the EPACT revises energy efficiency standards for buildings, promotes use of alternative fuels, and reduces the monopolistic structure of electric and gas utilities.

Figure 4.2 presents the total U.S. energy consumption distribution by major sectors for 1996. As indicated, buildings and industrial facilities are responsible, respectively, for 36 and 38% of the total U.S. energy consumption. The transportation sector, which accounts for the remaining 26% of the total U.S. energy consumption, uses mostly fuel products. However, buildings and industries consume predominantly electricity and natural gas. Because of its low price, coal is primarily used as an energy source for electricity generation.

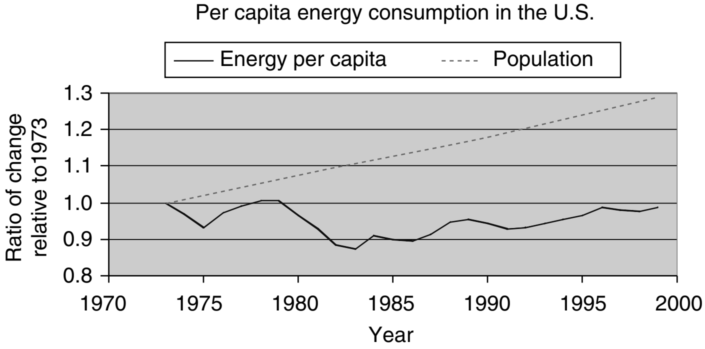

FIGURE 4.1 Per capita energy-use and population growth since 1973. (From EIA, *Annual Energy Review*, Department of Energy, Energy Information Administration, 1998. http://www.doe.eia.gov).

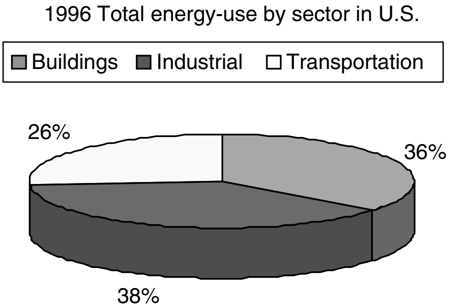

FIGURE 4.2 Distribution of U.S. energy consumption by end use sector. (From EIA, *Annual Energy Review*, Department of Energy, Energy Information Administration, 1998. http://www.doe.eia.gov).

Despite some improvements in energy efficiency over the last 25 years, the U.S. remains the most energy-intensive in the world. If it wants to maintain its lead in a global and competitive world economy, it is imperative that the U.S. continues to improve its energy efficiency.

In most countries, residential and commercial buildings account for a significant portion of the total national energy consumption (almost 40% in the U.S. and in France). Typically, buildings use electricity and a primary energy source such as natural gas or fuel oil. Electricity is used for lighting, appliances, and HVAC equipment. Typical energy density for selected types of commercial and institutional buildings are summarized in Table 4.1 for both the U.S. and France.

The industrial sector consumes more than 35% of the total U.S. energy-use as indicated in Figure 4.2. Fossil fuels constitute the main source for the U.S. industry. Electricity accounts for about 15% of the total U.S. industrial energy-use. In some energy-intensive manufacturing facilities, cogeneration systems are used to produce electricity from fossil fuels. A significant potential for energy savings exist in industrial facilities due to the vast amounts of energy wasted in the industrial processes. Using improved housekeeping measures and recovering some of the waste heat, the U.S. could save up to 35% of the total energy-used in the industry (Ross and Williams 1977).

The potential for energy conservation for both buildings and industrial sector remains large is the U.S. and other countries despite the improvements in the energy efficiency since the 1970s. Energy management programs using proven and systematic energy audit procedures suitable for both buildings and industrial facilities are provided in the following sections. In addition, some proven and cost-effective energy efficiency technologies are summarized.

TABLE 4.1 Energy Intensity by Principal Building Activity in kWh/m^2

Major Building Activity	France	US
Office	395	300
Education	185	250
Health care	360	750
Lodging	305	395
Food service	590	770
Mercantile and service	365	240
Sports	405	NA[a]
Public assembly	NA	375
Warehouse and storage	NA	125

[a] Not Available.

Source: From CEREN, *La Consommation d"Energie Dans les Regions Francaises*. Report from Centre d'Etudes et de Recherches Economiques sur l Energie 1997; Energy Information Administration (EIA), Annual Energy review. Department of Energy. 1998. http://www.doe.eia.gov (accessed on 2005).

4.3 Energy Audit Procedures

4.3.1 Energy Audit Types

Energy audits are the first step to improve the energy efficiency of buildings and industrial facilities. Generally, four types of energy audits can be distinguished as briefly described below (Krarti 2000):

- A walk-through audit consists typically of a short on-site visit of the facility to identify areas where simple and inexpensive actions (typically operating and maintenance measures) can provide immediate energy-use and/or operating cost savings.
- A utility cost analysis includes a careful evaluation of metered energy-uses and operating costs of the facility. Typically, the utility data over several years are evaluated to identify the patterns of energy-use, peak demand, weather effects, and potential for energy savings.
- A standard energy audit consists of a comprehensive energy analysis for the energy systems of the facility. In particular, the standard energy audit includes the development of a baseline for the energy-use of the facility, the evaluation of the energy savings, and the cost-effectiveness of appropriately selected energy conservation measures.
- A detailed energy audit is the most comprehensive but also time-consuming energy audit type. Specifically, the detailed energy audit includes the use of instruments to measure energy-use for the whole building and/or for some energy systems within the building (for instance by end uses such as lighting systems, office equipment, fans, chillers, etc.). In addition, sophisticated computer simulation programs are typically considered for detailed energy audits to evaluate and recommend energy retrofits for the facility.

4.3.2 General Procedure for a Detailed Energy Audit

To perform an energy audit, several tasks are typically carried out depending on the type of the audit and the size and function of the audited building. Some of the tasks may have to be repeated, reduced in scope, or even eliminated based on the findings of other tasks. Therefore, the execution of an energy audit is often not a linear process and is rather iterative. However, a general procedure can be outlined for most facilities.

Step 1: Facility and Utility Data Analysis. The main purpose of this step is to evaluate the characteristics of the energy systems and the patterns of energy-use for the building or the facility. The building/facility characteristics can be collected from the architectural/mechanical/electrical drawings and/or from discussions with building operators. The energy-use patterns can be obtained from a compilation of utility bills over several years. Analysis of the historical variation of the utility bills allows the energy auditor to determine if there are any seasonal and weather effects on the building energy-use. Some of the tasks that can be performed in this step are presented below with the key results expected from each task noted:

- Collect at least three years of utility data (to identify a historical energy-use pattern).
- Identify the fuel types used such as electricity, natural gas, oil, etc. (to determine the fuel type that accounts for the largest energy-use).
- Determine the patterns of fuel use by fuel type (to identify the peak demand for energy-use by fuel type).
- Understand utility rate structure (energy and demand rates) (to evaluate if the building is penalized for peak demand and if cheaper fuel can be purchased).
- Analyze the effect of weather on fuel consumption (to pinpoint any variations of energy-use related to extreme weather conditions).

- Perform utility energy-use analysis by building type and size; building signature can be determined including energy-use per unit area (to compare against typical indices).

Step 2: *Walk-Through Survey*. From this step, potential energy savings measures should be identified. The results of this step are important because they determine if the building warrants any further energy auditing work. Some of the tasks involved in this step are:

- Identify the customer concerns and needs.
- Check the current operating and maintenance procedures.
- Determine the existing operating conditions of major energy-use equipment (lighting, HVAC systems, motors, etc.).
- Estimate the occupancy, equipment, and lighting (energy-use density and hours of operation).

Step 3: *Baseline for Building Energy-Use*. The main purpose of this step is to develop a base-case model that represents the existing energy-use and operating conditions for the building. This model is to be used as a reference to estimate the energy savings incurred from appropriately selected energy conservation measures. The major tasks to be performed during this step are as follows:

- Obtain and review architectural, mechanical, electrical, and control drawings.
- Inspect, test, and evaluate building equipment for efficiency, performance, and reliability.
- Obtain all occupancy and operating schedules for equipment (including lighting and HVAC systems).
- Develop a baseline model for building energy-use.
- Calibrate the baseline model using the utility data and/or metered data.

Step 4: *Evaluation of Energy Savings Measures*. In this step, a list of cost-effective energy conservation measures is determined using both energy savings and economic analysis. To achieve this goal, the following tasks are recommended:

- Prepare a comprehensive list of energy conservation measures (using the information collected in the walk-through survey).
- Determine the energy savings due to the various energy conservation measures pertinent to the building using the baseline energy-use simulation model developed in phase 3.
- Estimate the initial costs required to implement the energy conservation measures.
- Evaluate the cost-effectiveness of each energy conservation measure using an economical analysis method (simple payback or life cycle cost analysis).

Table 4.2 and Table 4.3 provide summaries of the energy audit procedure recommended respectively for commercial buildings and for industrial facilities (Krarti 2000). Energy audits for thermal and electrical systems are separated because they are typically subject to different utility rates.

4.4 Energy Management Programs

This section describes energy conservation and energy efficiency programs that require energy auditing as a tool for proper and successful implementation and completion. These programs have been found to be effective in improving the energy efficiency of commercial buildings and industrial facilities.

4.4.1 Performance Contracting

Over the last decade, a new mechanism for funding energy projects has been proposed to improve energy efficiency of existing buildings. This mechanism, often called *performance contracting*, can be structured

TABLE 4.2 Energy Audit Summary for Residential and Commercial Buildings

Phase	Thermal Systems	Electric Systems
Utility analysis	Thermal energy-use profile (building signature)	Electrical energy-use profile (building signature)
	Thermal energy-use per unit area (or per student for schools or per bed for hospitals)	Electrical energy-use per unit area (or per student for schools or per bed for hospitals)
	Thermal energy-use distribution (heating, DHW, process, etc.)	Electrical energy-use distribution (cooling, lighting, equipment, fans, etc.)
	Fuel types used	Weather effect on electrical energy-use
	Weather effect on thermal energy-use	Utility rate structure (energy charges, demand charges, power factor penalty, etc.)
	Utility rate structure	
On-site survey	Construction Materials (thermal resistance type and thickness)	HVAC system type
	HVAC system type	Lighting type and density
	DHW system	Equipment type and density
	Hot water/steam use for heating	Energy-use for heating
	Hot water/steam for cooling	Energy-use for cooling
	Hot water/steam for DHW	Energy-use for lighting
	Hot water/steam for specific applications (hospitals, swimming pools, etc.)	Energy-use for equipment
		Energy-use for air handling
		Energy-use for water distribution
Energy-use baseline	Review architectural, mechanical, and control drawings	Review architectural, mechanical, electrical, and control drawings
	Develop a base-case model (using any baselining method ranging from very simple to more detailed tools)	Develop a base-case model (using any baselining method ranging from very simple to more detailed tools)
	Calibrate the base-case model (using utility data or metered data)	Calibrate the base-case model (using utility data or metered data)
Energy conservation measures	Heat recovery system (heat exchangers)	Energy-efficient lighting
	Efficient heating system (boilers)	Energy-efficient equipment (computers)
	Temperature setback	Energy-efficient motors
	EMCS	HVAC system retrofit
	HVAC system retrofit	EMCS
	DHW use reduction	Temperature setup
	Cogeneration	Energy-efficient cooling system (chiller)
		Peak demand shaving
		Thermal energy storage system
		Cogeneration
		Power factor improvement
		Reduction of harmonics

using various approaches. The most common approach for performance contacting consists of the following steps:

- A vendor or contractor proposes an energy project to a facility owner or manager after conducting an energy audit. This energy project would save energy-use and energy cost and thus would reduce the facility operating costs.
- The vendor/contractor funds the energy project using typically borrowed moneys from a lending institution.
- The vendor/contractor and facility owner/manager agree on a procedure to repay the borrowed funds from energy cost savings that may result from the implementation of the energy project.

An important feature of performance contracting is the need for a proven protocol for measuring and verifying energy cost savings. This measurement and verification protocol has to be accepted by all the parties involved in the performance contracting project: the vendor/contractor, the facility owner/manager, and the lending institution. For different reasons, all the parties have to insure that cost savings

TABLE 4.3 Energy Audit Summary for Industrial Facilities

Phase	Thermal Systems	Electric Systems
Utility analysis	Thermal energy-use profile (building signature)	Electrical energy-use profile (building signature)
	Thermal energy-use per unit of a product	Electrical energy-use per unit of a product
	Thermal energy-use distribution (heating, process, etc.)	Electrical energy-use distribution (cooling, lighting, equipment, process, etc.)
	Fuel types used	Analysis of the electrical energy input for specific processes used in the production line (such as drying)
	Analysis of the thermal energy input for specific processes used in the production line (such as drying)	
	Utility rate structure	Utility rate structure (energy charges, demand charges, power factor penalty, etc.)
On-site survey	List of equipment that use thermal energy	List of equipment thqt use electrical energy
	Perform heat balance of the thermal energy	Perform heat balance of the electrical energy
	Monitor thermal energy-use of all or part of the equipment	Monitor electrical energy-use of all or part of the equipment
	Determine the by-products of thermal energy-use (such emissions and solid waste)	Determine the by-products of electrical energy-use (such pollutants)
Energy-use baseline	Review mechanical drawings and production flow charts	Review electrical drawings and production flow charts
	Develop a base-case model using (any baselining method)	Develop a base-case model (using any baselining method)
	Calibrate the base-case model (using utility data or metered data)	Calibrate the base-case model (using utility data or metered data)
Energy conservation measures	Heat recovery system	Energy-efficient motors
	Efficient Heating and drying system	Variable speed drives
	EMCS	Air compressors
	HVAC system retrofit	Energy-efficient lighting
	Hot water and steam use reduction	HVAC system retrofit
	Cogeneration (possibly with solid waste from the production line)	EMCS
		Cogeneration (possibly with solid waste from the production line)
		Peak demand shaving
		Power factor improvement
		Reduction of harmonics

have indeed incurred from the implementation of the energy project and are properly estimated. Over the last decade, several methods and protocols for measuring and verifying actual energy savings from energy efficiency projects in existing buildings have been developed (Krarti 2000). Among the methods proposed for the measurement of energy savings are those proposed by the National Association of Energy Service Companies (NAESCO 1993), the Federal Energy Management Program (FEMP 1992), the American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE 1997), the Texas LoanSTAR program (Reddy, Kissock and Katipamula 1994), and the North American Energy Measurement and Verification Protocol (NEMVP) sponsored by DOE and later updated and renamed the International Performance Measurement and Verification Protocol (IPMVP 1997).

4.4.2 Commissioning of Building Energy Systems

Before final occupancy of a newly constructed building, it is recommended to perform commissioning of its various systems including structural elements, building envelope, electrical systems, security systems, and HVAC systems. The commissioning is a quality assurance process to verify and document the performance of building systems as specified by the design intent. During the commissioning process, operation and maintenance personnel are trained to properly follow procedures in order that all building systems are fully functional and are properly operated and maintained.

4.4.3 Energy Rating of Buildings

In the U.S., a new building rating system has been recently developed and implemented by the U.S. Green Building Council. This rating system is called the *Leadership in Energy and Environmental Design* (LEED), and it considers the energy and the environmental performance of all the systems in a building over its life cycle. Currently, the LEED rating system evaluates new and existing commercial, institutional, and high-rise residential buildings. The rating is based on credits that can be earned if the building satisfies a list of criteria based on existing proven technology. Different levels of green building certification are awarded based on the total credit earned.

Other countries have similar rating systems. In fact, England was the first country to develop and implement a national green building rating system, the Building Research Establishment's Environmental Assessment Method (BREEAM). The Building Research Establishment estimates that up to 30% of office buildings constructed in the last 7 years have been assessed using BREEAM rating system. Currently, BREEAM rating system can be applied to new and existing office buildings, industrial facilities, residential homes, and superstores.

4.5 Energy Conservation Measures

In this section energy conservation measures commonly implemented for commercial and industrial facilities are briefly discussed. The potential energy savings and the cost-effectiveness of some of the energy efficiency measures are discussed through illustrative examples. The calculation details of the energy savings incurred for common energy conservation measures can be found in Krarti (2000).

4.5.1 Building Envelope

For some buildings, the envelope (i.e., walls, roofs, floors, windows, and doors) has an important impact on the energy-used to condition the facility. The energy efficiency of the building envelope can be characterized by its building load coefficient (BLC). The BLC can be estimated either by a regression analysis of the utility data or by a direct calculation using the thermal resistance of the construction materials used in the building-envelope assemblies (i.e., walls, roofs, windows, doors, etc.). Figure 4.3 illustrates how the BLC for a given building can be estimated using utility data (Krarti 2000).

Some of the commonly recommended energy conservation measures to improve the thermal performance of the building envelope include the following:

1. *Addition of Thermal Insulation*. For building surfaces without any thermal insulation, this measure can be cost-effective.
2. *Replacement of Windows*. When windows represent a significant portion of the exposed building surfaces, using more energy-efficient windows (high R-value, low-emissivity glazing, air tight, etc.) can be beneficial in both reducing the energy-use and improving the indoor comfort level.
3. *Reduction of Air Leakage*. When infiltration load is significant, leakage area of the building envelope can be reduced by simple and inexpensive weather-stripping techniques. In residential buildings, the infiltration rate can be estimated using a blower door test setup as shown in Figure 4.4. The blower test door setup can be used to estimate the infiltration or exfiltration rates under both pressurization and depressurization conditions.

The energy audit of the envelope is especially important for residential buildings. Indeed, the energy-use from residential buildings are dominated by weather because heat gain and/or loss from direct conduction of heat or from air infiltration/exfiltration through building surfaces accounts for a major portion (50%–80%) of the energy consumption. For commercial buildings, improvements to the building envelope are often not cost-effective because modifications to the building envelope (replacing windows, adding thermal insulation in walls) are typically considerably expensive. However, it is recommended to

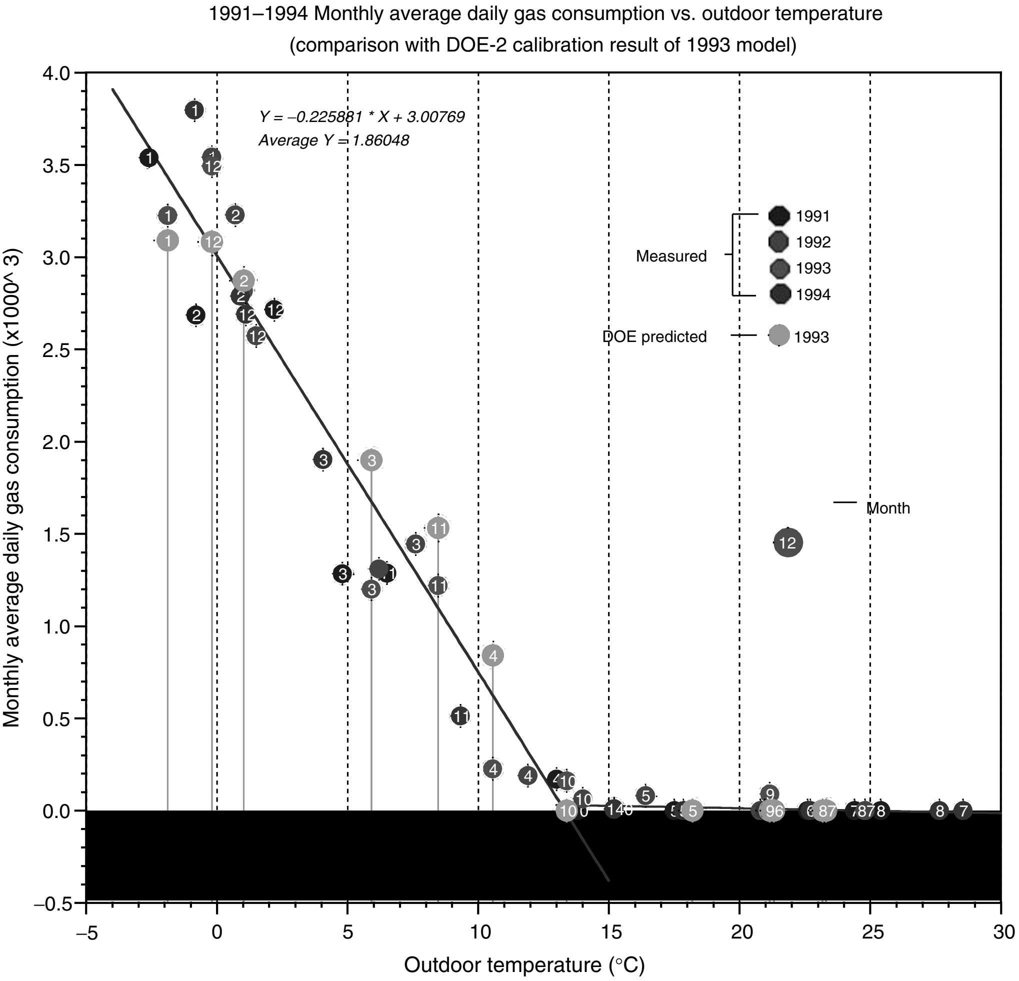

FIGURE 4.3 Estimation of the BLC based on a regression analysis of the monthly gas consumption. (From Krarti, M., *Energy Audit of Building Systems: An Engineering Approach*, CRC Press, Boca Raton, FL, 2000.)

systematically audit the envelope components not only to determine the potential for energy savings but also to insure the integrity of its overall condition. For instance, thermal bridges, if present, can lead to heat transfer increase and to moisture condensation. The moisture condensation is often more damaging and costly than the increase in heat transfer because it can affect the structural integrity of the building envelope.

4.5.2 Ventilation and Indoor Air Quality

4.5.2.1 Ventilation in Commercial/Institutional Buildings

The energy required to condition ventilation air can be significant in both commercial buildings and industrial facilities, especially in locations with extreme weather conditions. Whereas the ventilation is used to provide fresh air to occupants in commercial buildings, it is used to control the level of dust, gases, fumes, or vapors in several industrial applications. The auditor should estimate the existing volume of fresh air and compare this estimated amount of the ventilation air with that required by the

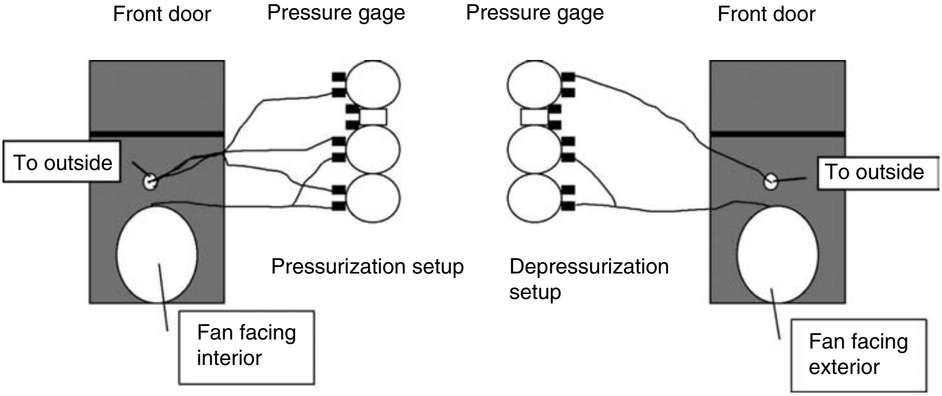

FIGURE 4.4 A blower door test setup for both pressurization and depressurization. (From Krarti, M., *Energy Audit of Building Systems: An Engineering Approach*, CRC Press, Boca Raton, FL, 2000.)

appropriate standards and codes. Excess in air ventilation should be reduced if it can lead to increases in heating and/or cooling loads. However, in some climates and periods of the year or the day, providing more air ventilation can be beneficial and may actually reduce cooling and heating loads through the use of air-side economizer cycles.

Table 4.4 summarizes some of the minimum outdoor air requirements for selected spaces in commercial buildings.

If excess ventilation air is found, the outside air damper setting can be adjusted to supply the ventilation that meets the minimum outside requirements as listed in Table 4.5. Further reductions in outdoor air can be obtained by using demand ventilation controls by supplying outside air only during periods when there is need for fresh air. A popular approach for demand ventilation is the monitoring of CO_2 concentration level within the spaces. CO_2 is considered as a good indicator of pollutants generated by occupants and other construction materials. The outside air damper position is controlled to maintain a CO_2 set-point within the space. CO_2-based demand-controlled ventilation has been implemented in various buildings with intermittent occupancy patterns including cinemas, theaters, classrooms, meeting rooms, and retail establishments. However, the ventilation for several office buildings has been controlled using CO_2 measurements (Emmerich and Persily 1997). Based on field studies, it has been found that significant energy savings can be obtained with a proper implementation of CO_2-based demand-controlled ventilation. Typically, the following building features are required for an effective performance of demand ventilation controls (Davidge 1991):

- Unpredictable variations in the occupancy patterns
- Requirement of either heating or cooling for most of the year
- Low pollutant emissions from non-occupant sources (i.e. furniture, equipment, etc.)

TABLE 4.4 Minimum Ventilation Rate Requirements for Selected Spaces in Commercial Buildings

Space and or Application	Minimum Outside Air Requirements
Office space	9.5 L/s (20 cfm) per person
Corridor	0.25 L/s per m^2 (0.05 cfm/ft.^{2})
Restroom	24 L/s (50 cfm) per toilet
Smoking lounge	28.5 L/s (60 cfm) per person
Parking garage	7.5 L/s (1.5 cfm/ft.^{2})

Source: From ASHRAE, *Ventilation for Acceptable Indoor Air Quality, Standard, 62*, American Society of Heating. Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 1989.

TABLE 4.5 Typical Efficiencies of Motors

Motor Size (HP)	Standard Efficiency	High Efficiency(%)
1	72%	81%
2	76%	84%
3	77%	89%
5	80%	89%
7.5	82%	89%
10	84%	89%
15	86%	90%
20	87%	90%
30	88%	91%
40	89%	92%
50	90%	93%

It should be noted that although CO_2 can be used to control occupant-generated contaminants, it may not reliably control pollutants generated from non-occupant sources such as building materials. As a solution, a base ventilation rate can be maintained at all times to ensure that non-occupant contaminants are controlled (Emmerich and Persily 1997).

4.5.2.2 Ventilation of Parking Garages

Automobile parking garages can be partially open or fully enclosed. Partially open garages are typically above-grade with open sides and do not generally need mechanical ventilation. However, fully enclosed parking garages are usually underground and require mechanical ventilation. Indeed, in absence of ventilation, enclosed parking facilities present several indoor air quality problems. The most serious is the emission of high levels of carbon monoxide (CO) by cars within the parking garages. Other concerns related to enclosed garages are the presence of oil and gasoline fumes, and other contaminants such as oxides of nitrogen (NO_x) and smoke haze from diesel engines.

To determine the adequate ventilation rate for garages, two factors are typically considered: the number of cars in operation and the emission quantities. The number of cars in operation depends on the type of the facility served by the parking garage and may vary from 3% (in shopping areas) up to 20% (in sports stadium) of the total vehicle capacity (ASHRAE 1999). The emission of carbon monoxide depends on individual cars including such factors as the age of the car, the engine power, and the level of car maintenance.

For enclosed parking facilities, ASHRAE standard 62-1989 specifies fixed ventilation rate of below 7.62 L/sm^2 (1.5 $cfm/ft.^2$) of gross floor area (ASHRAE 1989). Therefore, a ventilation flow of about 11.25 air changes per hour is required for garages with 2.5-m ceiling height. However, some of the model code authorities specify an air change rate of four to six air changes per hour. Some of the model code authorities allow ventilation rate to vary and be reduced to save fan energy if CO demand-controlled ventilation is implemented, that is, a continuous monitoring of CO concentrations is conducted, with the monitoring system being interlocked with the mechanical exhaust equipment. The acceptable level of contaminant concentrations varies significantly from code to code. A consensus on acceptable contaminant levels for enclosed parking garages is needed. Unfortunately, ASHRAE standard 62-1989 does not address the issue of ventilation control through contaminant monitoring for enclosed garages. Thus, ASHRAE commissioned a research project 945-RP (Krarti, Ayari, Grot 1999) to evaluate current ventilation standards and recommend rates appropriate to current vehicle emissions/usage. Based on this project, a general methodology has been developed to determine the ventilation requirements for parking garages.

Figure 4.5 indicates also the fan energy savings achieved by the on–off and VAV systems (relative to the fan energy use by the CV system). As illustrated in Figure 4.5, significant fan energy savings can be

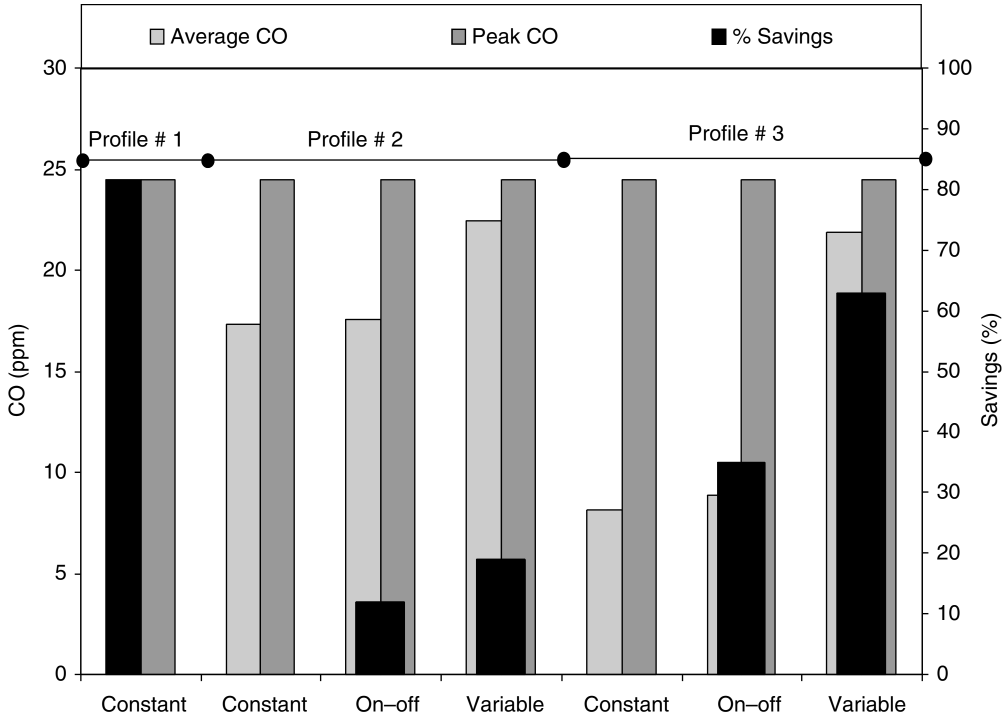

FIGURE 4.5 Typical energy savings and maximum CO level obtained for demand CO ventilation controls. (From Krarti, M., Ayari, A., and Grot, D., *Ventilation Requirements for Enclosed Vehicular Parking Garages*, Final Report for ASHRAE RP-945, American Society of Heating, Refrigerating, and Air Conditioning Engineering, Atlanta, GA, 1999.)

obtained when demand CO-ventilation control strategy is used to operate the ventilation system while also maintaining acceptable CO levels within the enclosed parking facility. These energy savings depend on the pattern of car movement within the parking facility. Figure 4.6 indicates three types of car movement profiles considered in the analysis considered by Krarti, Ayari and Grot (1999).

4.5.3 Electrical Systems

For most commercial buildings and a large number of industrial facilities, the electrical energy cost constitutes the dominant part of the utility bill. Lighting, office equipment, and motors are the electrical systems that consume the major part of energy in commercial and industrial buildings.

4.5.3.1 Lighting

For a typical office building lighting represents on average 40% of the total electrical energy-use. There are a variety of simple and inexpensive measures to improve the efficiency of lighting systems. These measures include the use of energy-efficient lighting lamps and ballasts, the addition of reflective devices, delamping (when the luminance levels are above the recommended levels by the standards), and the use of daylighting controls. Most lighting measures are especially cost-effective for office buildings for which payback periods are less than one year.

4.5.3.2 Daylighting

Several studies indicated that daylighting can offer a cost-effective alternative to electrical lighting for commercial and institutional buildings. Through sensors and controllers, daylighting can reduce and even eliminate the use of electrical lighting required to provide sufficient illuminance levels inside office

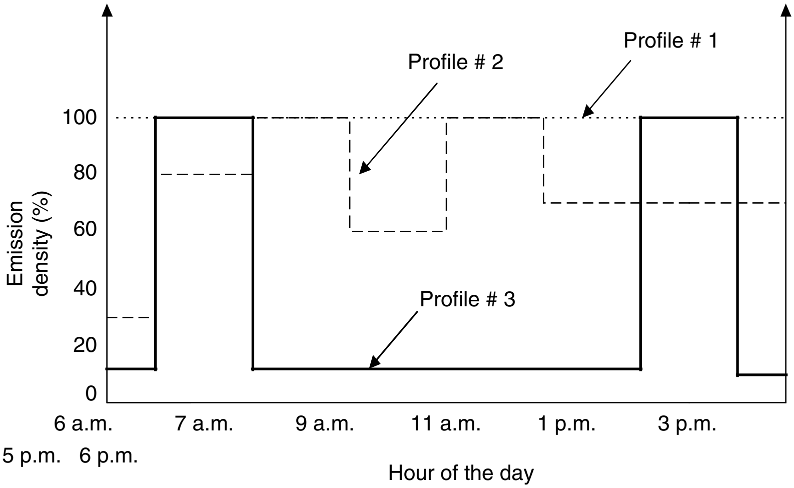

FIGURE 4.6 Car movement profiles used in the analysis conducted by Krarti et al. (From Krarti, M., Ayari, A., and Grot, D., *Ventilation Requirements for Enclosed Vehicular Parking Garages*, Final Report for ASHRAE RP-945, American Society of Heating, Refrigerating, and Air Conditioning Engineering, Atlanta, GA, 1999.)

spaces. Recently, a simplified calculation method has been developed by Krarti, Erickson and Hillman (2005) to estimate the reduction in the total lighting energy-use due to daylighting with dimming controls for office buildings. The method has been shown to apply for office buildings in the U.S. as well as in Egypt (Al-Moheimen, Hanna and Krarti 2005). The simplified calculation method is easy to use and can be applied as a predesign tool to assess the potential of daylighting in saving electricity use associated with artificial lighting for office buildings.

To determine the percent savings, f_d, in annual use of artificial lighting due to implementing daylighting using daylighting controls in office buildings, Krarti, Erickson and Hillman (2005) found that the following equation can be used:

$$f_\mathrm{d} = b[1 - \exp(-a\tau_\mathrm{w} A_\mathrm{w}/A_\mathrm{p})]\frac{A_\mathrm{p}}{A_\mathrm{f}}, \tag{4.1}$$

where A_w/A_p is the window-to-perimeter floor area; this parameter provides a good indicator of the window size relative to the daylit floor area. A_p/A_f is the perimeter-to-total floor area; this parameter indicates the extent of the daylit area relative to the total building floor area. Thus, when $A_p/A_f = 1$, the whole building can benefit from daylighting. Parameters a and b in Equation 4.1 are coefficients that depends only on the building location and are given by Table 4.6 for various sites throughout the world.

4.5.3.3 Office Equipment

Office equipment constitutes the fastest growing part of the electrical loads, especially in commercial buildings. Office equipment includes computers, fax machines, printers, and copiers. Today, there are several manufacturers that provide energy-efficient office equipment (such those that comply with the U.S. EPA Energy Star specifications). For instance, energy-efficient computers automatically switch to a low-power "sleep" mode or off-mode when not in use.

4.5.3.4 Motors

The energy cost to operate electric motors can be a significant part of the operating budget of any commercial and industrial building. Measures to reduce the energy cost of using motors include reducing operating time (turning off unnecessary equipment), optimizing motor systems, using controls to match

TABLE 4.6 Coefficients *a* and *b* of Equation 4.1 for Various Locations throughout the World

Location	*a*	*b*	Location	*a*	*b*
Atlanta	19.63	74.34	Casper	19.24	72.66
Chicago	18.39	71.66	Portland	17.79	70.93
Denver	19.36	72.86	Montreal	18.79	69.83
Phoenix	22.31	74.75	Quebec	19.07	70.61
New York City	18.73	66.96	Vancouver	16.93	68.69
Washington DC	18.69	70.75	Regina	20.00	70.54
Boston	18.69	67.14	Toronto	19.30	70.48
Miami	25.13	74.82	Winnipeg	19.56	70.85
San Francisco	20.58	73.95	Shanghai	19.40	67.29
Seattle	16.60	69.23	K-Lumpur	20.15	72.37
Los Angels	21.96	74.15	Singapore	23.27	73.68
Madison	18.79	70.03	Cairo	26.98	74.23
Houston	21.64	74.68	Alexandria	36.88	74.74
Fort Worth	19.70	72.91	Tunis	25.17	74.08
Bangor	17.86	70.73	Sao Paulo	29.36	71.19
Dodge City	18.77	72.62	Mexico91	28.62	73.63
Nashville	20.02	70.35	Melbourne	19.96	67.72
Oklahoma City	20.20	74.43	Roma	16.03	72.44
Columbus	18.60	72.28	Frankfurt	16.22	69.69
Bismarck	17.91	71.50	Kuwait	21.98	65.31
Minneapolis	18.16	71.98	Riyadh	21.17	72.69
Omaha	18.94	72.30			

Source: From Krarti, M., Erickson, P., and Hillman. T., *Daylighting Building and Environment*, 40, 747–754, 2005.

motor output with demand, using variable speed drives for air and water distribution, and installing energy-efficient motors. Table 4.5 provides typical efficiencies for several motor sizes.

In addition to the reduction in the total facility electrical energy-use, retrofits of the electrical systems decrease space cooling loads and therefore further reduce the electrical energy-use in the building. These cooling energy reductions as well as possible increases in thermal energy-use (for space heating) should be accounted for when evaluating the cost-effectiveness of improvements in lighting and office equipment.

4.5.4 HVAC Systems

The energy-use due to HVAC systems can represent 40% of the total energy consumed by a typical commercial building. A large number of measures can be considered to improve the energy performance of both primary and secondary HVAC systems. Some of these measures are listed below:

- *Setting Up/Back Thermostat Temperatures*. When appropriate, setback of heating temperatures can be recommended during unoccupied periods. Similarly, setup of cooling temperatures can be considered.
- *Retrofit of Constant-Air-Volume Systems*. For commercial buildings, variable-air-volume (VAV) systems should be considered when the existing HVAC systems rely on constant volume fans to condition part or the entire building.
- *Retrofit of Central Heating Plants*. The efficiency of a boiler can be drastically improved by adjusting the fuel air ratio for proper combustion. In addition, installation of new energy-efficient boilers can be economically justified when old boilers are to be replaced.
- *Retrofit of Central Cooling Plants*. Currently, there are several chillers that are energy-efficient, easy to control and operate, and are suitable for retrofit projects. In general, it is cost-effective to recommend energy-efficient chillers such as those using scroll compressors for replacement of existing chillers.

- *Installation of Heat Recovery Systems*. Heat can be recovered from some HVAC equipment. For instance, heat exchangers can be installed to recover heat from air handling unit (AHU) exhaust air streams and from boiler stacks.

It should be noted that there is a strong interaction between various components of heating and cooling system. Therefore, a whole-system analysis approach should be followed when retrofitting a building HVAC system. Optimizing the energy-use of a central cooling plant (which may include chillers, pumps, and cooling towers) is one example of using a whole-system approach to reduce the energy-use for heating and cooling buildings.

4.5.5 Compressed-Air Systems

Compressed air has become an indispensable tool for most manufacturing facilities. Its uses span a range of instruments from air-powered hand tools and actuators to sophisticated pneumatic robotics. Unfortunately, staggering amounts of compressed air are currently wasted in a large number of facilities. It is estimated that only 20%–25% of input electrical energy is delivered as useful compressed-air energy. Leaks are reported to account for 10%–50% of the waste and misapplication accounts for 5–40% of loss in compressed air (Howe and Scales 1998).

The compressor can be selected from several types such as centrifugal, reciprocating, or rotary screw with one or multiple stages. For small and medium sized units, screw compressors are currently the most commonly used in the industrial applications. Table 4.7 provides typical pressure, airflow rate, and mechanical power requirement ranges for different types of compressors.

Some of the energy conservation measures that are suitable for compressed-air systems are listed below:

- Repair of air leaks in the distribution lines. Several methods do exist to detect these leaks ranging from the use of water and soap to the use of sophisticated equipment such as ultrasound leak detectors.
- Reduction of inlet air temperature and/or the increase of inlet air pressure.
- Reduction of the compressed-air usage and air pressure requirements by making some modifications to the processes.
- Installation of heat recovery systems to use the compression heat within the facility for either water heating or building space heating.
- Installation of automatic controls to optimize the operation of several compressors by reducing part load operations.
- Use of booster compressors to provide higher discharge pressures. Booster compressors can be more economical if the air with the highest pressure represents a small fraction of the total compressed air used in the facility. Without booster compressors, the primary compressor will have to compress the entire amount of air to the maximum desired pressure.

TABLE 4.7 Typical Ranges of Application for Various Types of Air Compressors

Compressor Type	Airflow Rate (m^3/s)	Absolute Pressure (MPa)	Mechanical power requirement (kW/L/s)
Reciprocating	0.0–5.0	0.340–275.9	0.35–0.39
Centrifugal	0.5–70.5	3.5–1034.3	0.46
Rotary screw	0.5–16.5	0.1–1.8	0.33–0.41

Source: From Herron, D. J., *Energy Engineering*, 96(2), 19, 1999.

4.5.6 Energy Management Controls

With the constant decrease in the cost of computer technology, automated control of a wide range of energy systems within commercial and industrial buildings is becoming increasingly popular and cost-effective. An energy management and control system (EMCS) can be designed to control and reduce the building energy consumption within a facility by continuously monitoring the energy-use of various equipments and making appropriate adjustments. For instance, an EMCS can automatically monitor and adjust indoor ambient temperatures, set fan speeds, open and close air handling unit dampers, and control lighting systems.

If an EMCS is already installed in the building, it is important to recommend a system tune-up to insure that the controls are properly operating. For instance, the sensors should be calibrated regularly in accordance with manufacturer specifications. Poorly calibrated sensors may cause increase in heating and cooling loads and may reduce occupant comfort.

Precooling building thermal mass is an example of the application of the EMCS to reduce operating costs. Precooling of the building thermal mass can be effective at lowering building operating costs. This strategy can have a large impact when chillers have high loads during periods of high occupancy and high outdoor temperatures (which typically coincide with on-peak periods in rate structures). By reducing the on-peak cooling load, it is possible to reduce chiller energy-use during these critical periods, thereby reducing energy costs.

Based on long-term simulation analysis, the annual energy cost savings associated with precooling has been estimated for various time-of-use utility rates (Morgan and Krarti 2005). For time-of-use rates, on-peak to off-peak ratios for energy and demand charges were defined as follows:

For the ratio of on-peak to off-peak energy charges, R_e:

$$R_e = \frac{(\text{PeakEnergyRate/kWh})}{\text{Off} - \text{Peak Energy Rate(/kWH)}.} \tag{4.2}$$

For the ratio of on-peak to off-peak demand charges, R_d:

$$R_d = \frac{(\text{PeakDemandRate/kW})}{\text{Off} - \text{Peak Demand Rate(/kW)}.} \tag{4.3}$$

Figure 4.7 and Figure 4.8 show the variation of the annual energy cost savings for a typical office building located in four U.S. locations due to a 4-h precooling period as a function of R_d and R_e, respectively. The office building has a heavy thermal mass of 105 lbm/ft.^{2} (513.7 kg/m^2) and the time-of-use rate has an 8-h on-peak period (Morgan and Krarti 2005).

4.5.7 Indoor Water Management

Water and energy savings can be achieved in buildings by using water-saving fixtures instead of the conventional fixtures for toilets, faucets, showerheads, dishwashers, and clothes washers. Savings can also be achieved by eliminating leaks in pipes and fixtures.

Table 4.8 provides typical water use of conventional and water-efficient fixtures for various end uses. In addition, Table 4.8 indicates the hot water use by each fixture as a fraction of the total water. With water-efficient fixtures, savings of 50% of water use can be achieved for toilets, showers, and faucets.

4.5.8 New Technologies

The energy auditor may consider the potential of implementing and integrating new technologies within the facility. It is therefore important that the energy auditor understands these new technologies and knows how to apply them. The following listing includes new technologies that can be considered for commercial and industrial buildings:

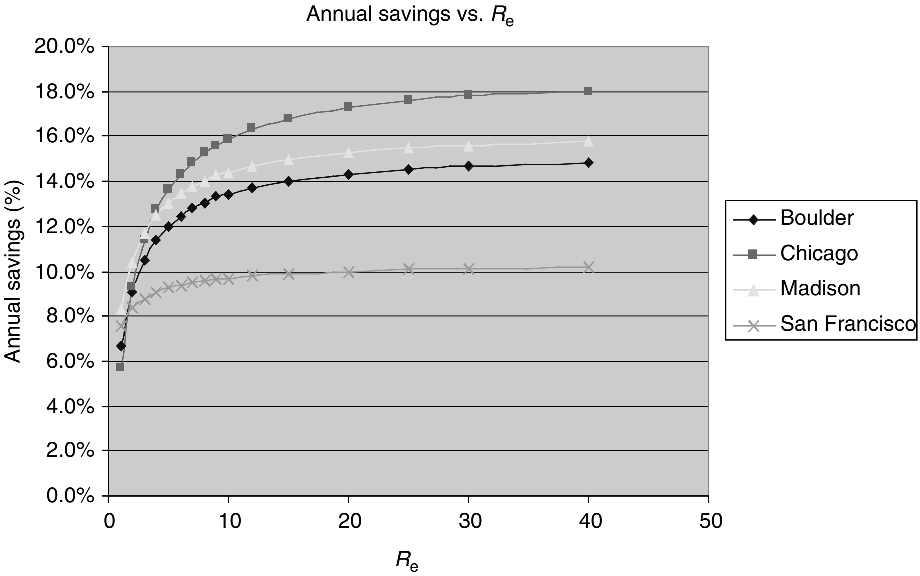

FIGURE 4.7 Annual energy cost savings due to precooling relative to conventional controls as a function of R_e. (From Morgan, S. and Krarti, M., *Impact of Electricity Rate Structures on the Energy Cost Savings of Precooling Controls for Office Buildings*, *Building and Environment* submitted, 2005.)

1. *Building-Envelope Technologies*. Recently several materials and systems have been proposed to improve the energy efficiency of building envelope and especially windows including:
    - Spectrally selective glasses that can optimize solar gains and shading effects
    - Chromogenic glazings that change their properties automatically depending on temperature and/or light level conditions (similar to sunglasses that become dark in sunlight)

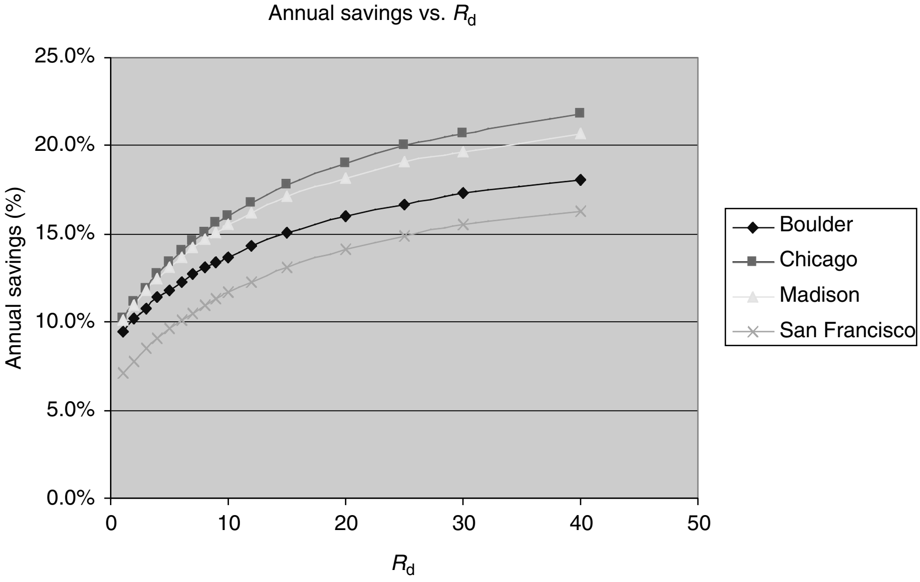

FIGURE 4.8 Annual energy cost savings due to precooling relative to conventional controls as a function of R_d. (From Morgan, S. and Krarti, M., *Impact of Electricity Rate Structures on the Energy Cost Savings of Precooling Controls for Office Buildings*, *Building and Environment* submitted, 2005.)

TABLE 4.8 Usage Characteristics of Water-Using Fixtures

End-Use	Conventional Fixtures	Water-Efficient Fixtures	Usage Pattern	% Hot Water
Toilets	3.5 gal/flush	1.6 gal/flush	4 flushes/pers/day	0%
Showers	5.0 gal/min	2.5 gal/min	5 min./shower	60%
Faucets	4.0 gal/min	2.0 gal/min	2.5 min/pers/day	50%
Dishwashers	14.0 gal/load	8.5 gal/load	0.17 loads/pers/day	100%
Clothes washers	55.0 gal/load	42.0 gal/load	0.3 loads/pers/day	25%
Leaks	10% of total use	2% of total use	N/A	50%

Source: From Krarti, M., *Energy Audit of Building Systems: An Engineering Approach*, CRC Press, Boca Raton, 2000.

  - Building integrated photovoltaic panels that can generate electricity while absorbing solar radiation and reducing heat gain through building envelope (typically roofs)
2. *Light-Pipe Technologies*. Although the use of daylighting is straightforward for perimeter zones that are near windows, it is not usually feasible for interior spaces, particularly those without any skylights. Recent but still emerging technologies allow the “piping” of light from roof or wall-mounted collectors to interior spaces that are not close to windows or skylights.
3. *HVAC Systems and Controls*. Several strategies can be considered for energy retrofits including:
    - Thermal comfort controls can reduce energy consumption for heating or cooling buildings. Some HVAC control manufacturers have recognized the potential benefits from thermal comfort controls—rather than controls relying on only dry-bulb temperature—and have already developing and producing thermal comfort sensors. These sensors can be used to generate comfort indicators such as predicted mean vote (PMV) and/or predicted percent dissatisfied (PPD).
    - Heat recovery technologies, such rotary heat wheels and heat pipes, can recover 50–80% of the energy-used to heat or cool ventilation air supplied to the building.
    - Desiccant-based cooling systems are now available and can be used in buildings with large dehumidification loads during long periods (such as hospitals, swimming pools, and supermarket fresh produce areas).
    - Geothermal heat pumps can provide an opportunity to take advantage of the heat stored underground to condition building spaces.
    - Thermal energy storage (TES) systems offer a means of using less expensive off-peak power to produce cooling or heating to condition the building during on-peak periods. Several optimal control strategies have been developed in recent years to maximize the cost savings of using TES systems.
4. *Cogeneration*. This is not really a new technology. However, recent improvements in its combined thermal and electrical efficiency made cogeneration cost-effective in several applications, including institutional buildings such hospitals and universities.

4.6 Summary

In this chapter, simple yet proven analysis, procedures, and technologies have been described to improve energy efficiency for buildings and industrial facilities. If the energy management procedures are followed properly and if some cost-effective energy conservation measures—briefly described in this chapter—are implemented, it is expected that significant savings in energy-use and cost can be achieved. The efficient use of energy will continue to be vital to improve the environment and to increase the economic competitiveness.

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5

Electrical Energy Management in Buildings

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5.1 Principal Electricity Uses in Buildings

5.1.1 Introduction: The Importance of Energy Efficiency in Buildings

A typical building is designed for a forty-year economic life. This implies that the existing inventory of buildings—with all their good and bad features—is turned over very slowly. Today, we know it is cost-effective to design a high degree of energy efficiency into new buildings because the savings on operating and maintenance costs will repay the initial investment many times over. Many technological advances have occurred in the last two decades, resulting in striking reductions in the energy usage required to operate buildings safely and comfortably. An added benefit of these developments is the reduction in air pollution, which has occurred as a result of generating less electricity.

There are hundreds of building types, and buildings can be categorized in many ways: by use, type of construction, size, thermal characteristics, etc. For simplicity, two designations will be used here: residential and nonresidential.

The residential category includes features common to single-family dwellings, apartments, and hotels. In 2001, there were 107 million housing units in the U.S. The nonresidential category mainly emphasizes office buildings, but also includes a less detailed discussion of features common to retail stores, hospitals, restaurants, and laundries. There are approximately 5 million commercial buildings, totaling 72 billion ft.^{2}, in the U.S. (2001 data). Most of this space is contained in buildings larger than 10,000 ft.^{2}. Industrial facilities are not included here, but are discussed in Chapter 10. The extension to other types is either obvious, or can be pursued by referring to the literature.

Total energy consumption in the two sectors has evolved as follows since the previous two editions of this book (1 quad = 10^{15} BTU):

	Year		
	1975 (quads)	1992 (quads)	2004 (quads)
Residential	—	16.8	21.2
Commercial	—	12.9	17.5
Total	25.1	29.7	38.7

There has been a remarkable shift in the residential and commercial sectors since 1975. The use of natural gas, which increased rapidly in these sectors prior to 1975, flattened out and has remained essentially constant. The use of petroleum has decreased. The biggest change has been the dramatic increase in electricity use, which doubled from 1975 to 2004.

The approach taken in this chapter is to list two categories of specific strategies that are cost-effective methods for conserving electricity. The first category includes those measures that can be implemented at low capital cost using existing facilities and equipment in an essentially unmodified state. The second category includes technologies that require retrofitting, modification of existing equipment, or new equipment or processes. Generally, moderate to substantial capital investments are also required.

5.1.2 Electricity Use in Residential and Commercial Buildings

Table 5.1 summarizes electricity consumption data by major end use for the residential and commercial sectors. The data are from the Energy Information Administration's (EIA's) most recently available energy consumption surveys that took place in 2001 for the residential sector and 1999 for the commercial sector.

The single most significant residential end use of electricity is space cooling (16.1%), followed by refrigeration (13.7%), space heating (10.2%), water heating (9.1%) and lighting (8.8%). The combination of other uses, such as entertainment systems, personal computers, printers, etc., is also substantial, accounting for one-quarter of residential electricity use. In the commercial sector, space conditioning, i.e., the combination of heating, ventilating, and air conditioning (HVAC), uses of the most electricity, accounting for 37.9%. Space cooling accounts for the majority of space conditioning electricity use; indeed, by itself, space cooling represents one-quarter of all commercial electricity use. The next two largest end users of electricity in the commercial sector are lighting at 23.1% and office equipment at 17.9%.

5.1.2.1 Residential Electricity Use

Space conditioning is the most significant end use of electricity in residential buildings, accounting for approximately one-quarter of total electricity use. Electricity is used in space heating and cooling to drive fans and compressors, to provide a direct source of heat (resistance heating), to provide an indirect source of heat or "cool" (heat pumps), and for controls.

At 8.8% in 2001, residential lighting electricity use was down from 10% in the 1980s due to the introduction of more efficient lamps, principally compact fluorescents, as well as to a greater share of electricity being consumed by other end uses. The bulk of residential lighting is still incandescent, and offers substantial opportunities for improved efficiency.

The share of residential electricity used by water heating has also decreased during the last decade. At 9.1% in 2001, it is down from 10.7% in 1992. Electricity use for this purpose currently occurs in regions where there is cheap hydroelectricity, or where alternative fuels are not available. Solar water heating is another alternative that is used on a limited basis.

TABLE 5.1 Electricity Consumption by End Use in the Residential and Commercial Sectors

End Use	Residential Sector, 2001 (billion kWh)	Percent of Total Residential Electricity Use (%)	Commercial Sector, 1999 (billion kWh)	Percent of Total Commercial Electricity Use (%)
Space Heating	116	10.2	45	5.0
Space Cooling	183	16.1	232	25.6
Ventilation	[a]	[a]	66	7.3
Water Heating	104	9.1	11	1.2
Refrigeration	156	13.7	78	8.6
Cooking	80	7.0	19	2.1
Clothes Washers & Dryers	76	6.7	[a]	[a]
Freezers	39	3.4	[a]	[a]
Lighting	101	8.8	210	23.1
Office Equipment	[a]	[a]	163	17.9
Other Uses	285	25.0	84	9.2
Total	1,140	100	908	100

[a] Included in “Other Uses”.

Source: From Energy Information Administration, Residential Energy Consumption Survey, 2001; Energy Information Administration, Commercial Building Energy Consumption Survey, 1999.

Refrigerators are another important energy end use in the residential sector, accounting for 13.7% of residential electricity consumption in 2001. For the last 40 years, virtually every home in the U.S. has had a refrigerator. Therefore, refrigerators have fully penetrated the residential sector for some time. However, significant changes related to energy use have occurred during this period as new standards have been implemented. For one, the average size of refrigerators has more than doubled from less than 10 $ft.^3$ in 1947 to over 20 $ft.^3$ in recent years. Meanwhile, the efficiency of refrigerators has increased dramatically. In the early 1960s, average electricity consumption of a new refrigerator was around 1000 kWh/year, and they were about 12 $ft.^3$ (adjusted volume). Since 2001, new refrigerators consume less than 500 kWh/year and have adjusted volumes around 20 $ft.^3$. The net result is that current refrigerators, although 70% larger than those forty years ago, consume about 50% less electricity.

Cooking, clothes washing and drying, and freezers account for another 17.1%, while “other” uses (including home entertainment systems, personal computers, and miscellaneous items) make up the balance (25%) of electricity used in the residential sector. Computers and other consumer electronic devices, such as VCRs, DVD players, and electronic gaming systems, have proliferated in homes during the last few decades. For example, only 8% of households had personal computers (either desktop or laptop) in 1984, whereas 51% had desktops and 13% had laptops in 2001. The energy used by personal computers is continuing to rise. The EIA estimates that energy use by PCs increased by 9% between 2001 and 2005, and that it will increase by 29% between 2005 and 2010.

5.1.2.2 Nonresidential Electricity Use

For the commercial sector as a whole, HVAC dominates electricity use. In most nonresidential buildings where space conditioning is used, HVAC is the major electricity end use. There are exceptions of course—in energy-intensive facilities such as laundries, the process energy will be most important. Electricity is used in space conditioning to run fans, pumps, chillers, and cooling towers. Other uses include electric resistance heating (for example, in terminal reheat systems) or electric boilers.

Nonresidential lighting is generally next in importance to HVAC in regards to electricity use, except in those nonresidential facilities with energy-intensive processes. In a typical office building, lighting consumes nearly one-quarter of the electricity. Interior lighting in the commercial sector is generally fluorescent, with a growing use of metal halide lamps, and with a small fraction of incandescent lamps. High-efficiency fluorescent lamps, electronic ballasts, compact fluorescent lamps and improved lighting controls are now the norm. Incandescent lamps still see major use in retail for display lighting, as well as in older buildings, or for decorative or esthetic applications. The EIA's *Commercial Building Energy Consumption Surveys* in 1992 and 1999 show that the percentage of commercial building electricity use consumed by lighting dropped from 27.7% in 1992 to 23.1% in 1999. Furthermore, the EIA's *Annual Energy Outlook 2005* predicts that lighting's share of commercial building electricity use will continue to drop, reaching an estimated 21.4% by 2025.

Water heating is another energy use in nonresidential buildings, but here circulating systems (using a heater, storage tank, and pump) are more common. Many possibilities exist for using heat recovery as a source of hot water. The amount of electricity used for water heating in commercial buildings has remained relatively consistent at a little over 1% during the last decade. However, the EIA predicts electricity use for water heating may increase to 2.3% by 2025.

Refrigeration is an important use of energy in supermarkets and several other types of nonresidential facilities. It is now common practice to include heat recovery units on commercial refrigeration systems. As in residential applications, commercial refrigeration electricity use has decreased in the past few decades due to efficiency gains. For example, in 1999 refrigeration accounted for 8.6% of commercial electricity use, down from 10.1% in 1992. EIA predictions estimate refrigeration will only represent 3.9% in 2025.

Commercial electricity use by office equipment has increased substantially since the last edition of this handbook; it grew from 6.7% in 1992 to 17.9% in 1999. Much of this increase is due to a greater use of computers. For larger computing units used in central data processing systems, specially designed rooms with temperature and humidity control are required. As a rule of thumb, the electricity used by the computer must be at least doubled because cooling must be provided to remove the heat from the equipment, lights, and personnel. Now, with the trend toward the widespread use of microcomputers, special space conditioning is not required. But, the sheer numbers of computers increase the air conditioning load and electrical demand.

These, with their peripheral equipment including printers, scanners, and data storage systems, have grown rapidly in the last decade. Electronic mail and Internet conferencing is displacing other communication systems. For the commercial sector as a whole, 431 out of every 1000 employees in 1992 had a computer, compared with 707 out of every 1000 employees in 1999. The ratio of computers to employees is even higher in office buildings. In 1992, there were 6 computers to every 10 employees, while, in 1999, there were 9.5 computers to every 10 employees.

In nonresidential facilities, the balance of the electricity use is for elevators, escalators, and miscellaneous items.

5.2 Strategies for Electricity End-Use Management

5.2.1 Setting up an Energy Management Program

The general procedure for establishing an energy management program in buildings involves five steps:

- Review historical energy use.
- Perform energy audits.
- Identify energy management opportunities.
- Implement changes to save energy.
- Monitor the energy management program, set goals, and review progress.

Each step will be described briefly.

5.2.1.1 Review of Historical Energy Use

Utility records can be compiled to establish electricity use for a recent 12-month period. These should be graphed on a form (see Figure 5.1) so annual variations and trends can be evaluated. By placing several

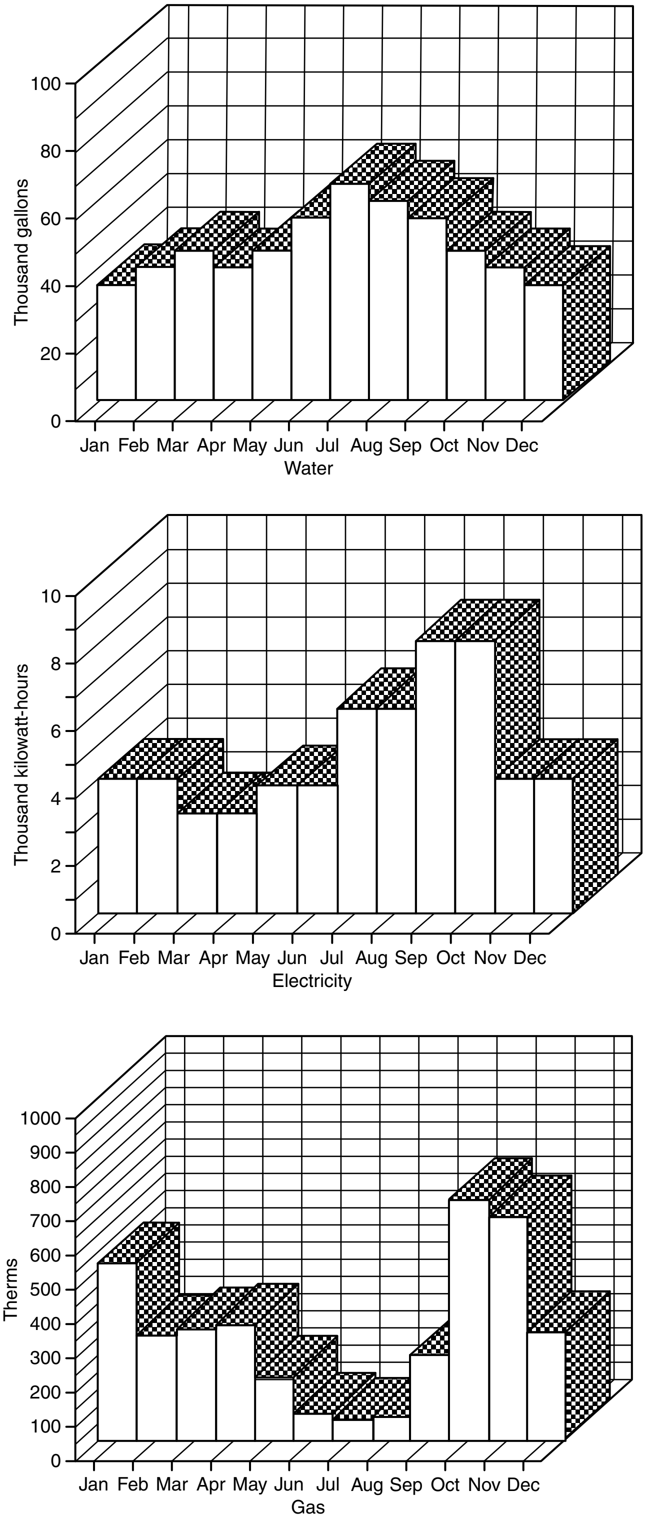

FIGURE 5.1 Sample graph: Historial energy use in an office building.

Building description

- Name:______________ Age: ___years heating degree days ____
- Location: ____
- No. of floors____Gross floor area___ m^2 (ft.^{2}) Net floor area___m^2(ft.^{2})
- Percentage of surface area which is glazed ___% cooling degree days _____
- Type of air conditioning system; heating only ____ evaporative _____ dual duct ____ other (describe) ______________________________
- Percentage breakdown of lighting equipment: Incandescent ______%

Building mission

- What is facility used for:
- Full time occupancy (employees) ____ persons
- Transient occupancy (visitors or public) ____ persons
- Hours of operations per year ______
- Unit of production per year ____ Unit is _______

Installed capacity

- Total installed capacity for lighting ____kW
- Total installed capacity of electric drives greater than 7.5 kW (10hp) (motors, pumps, fans, elevators, chillers, etc.)____hp × 0.746=____kW
- Total steam requirements _____lbs/day or ____kg/day
- Total gas requirements ___ft.^{3}/day or BTU/hr or ____m^3/day
- Total other fuel requirements ____

Annual energy end use

Energy form × conversion			kBTU/yr	metric units		Conversion MJ/yr	
• Electricity	__kWh/yr	× 3.41	= _____	_____ kWh/yr	×	3.6	= _______
• Steam	__lb/yr	× 1.00	= _____	_____ kg/yr	×	2.32	= _______
• Natural gas	__cf/yr	× 1.03	= _____	_____ m^3/yr	×	38.4	= _______
• Oil	__gls/yr	× {#2 139 #6 150}	= _____	_____ l/yr	×	{#2 38.9 #6 41.8}	= _______
• Coal	__tons/yr	× 24,000	= _____	_____ kg/yr	×	28.0	= _______
• Other	__	×	= _____	_____	×		= _______
	Totals		_____				_______

Energy use performance factors (EUPF's) for building

- EUPF 1 = MJ/yr (kBTU/yr) ÷ Net floor area = _______ MJ/m^2yr (kBTU/ft.^{2}yr)
- EUPF 2 = MJ/yr (kBTU/yr) ÷ Average annual occupancy = _______ MJ/person ·yr) (kBTU/person ·yr)
- EUPF 3 = MJ/yr (kBTU/yr) ÷ Annual units of production = _______ MJ/unit ·yr) (kBTU/unit ·yr)

FIGURE 5.2 Building energy survey form.

years (e.g. last year, this year, and next year projected) on the form, past trends can be reviewed and future electricity use can be compared with goals. Alternatively, several energy forms can be compared for energy use vs. determined production (e.g., meals served for a restaurant, or kilograms of laundry washed for a laundry, etc.).

5.2.1.2 Perform Energy Audits

Figure 5.2 and Figure 5.3 are data sheets used in performing an energy audit of a building. The building energy survey form, Figure 5.2, provides a gross indication of how energy is used in the building in meeting the particular purpose for which it was designed. This form would not be applicable to single-family residences, but it could be used with apartments. It is primarily intended for commercial buildings.

Figure 5.3 is a form used to gather information concerning energy used by each piece of equipment in the building. When totaled, the audit results can be compared with the historical energy use records plotted on Figure 5.1. The energy audit results show a detailed breakdown and permit identification of major energy-using items.

Facility name ______________
Location ______________
Symbol: K = 10^3 M = 10^3

Date ______________ By __________ Sheet ___ of ___
Period of survey: 1 day 1wk 1mo 1yr
Notes ________________________________

Conversion factors

Multiply	by	to get
kWh	306	MJ
BTU/hr	0.000293	kW
hp	0.746	kW

Item no.	Equipment description	Power			Est. hrs use per period	kWh	Conv. factor	Total energy use per period (MJ)
		Name plate rating (BTU/hr,kW, hp,etc,)	Conv. factor to kW	Est.% load (100%,50%, etc.)				

FIGURE 5.3 Energy audit data sheet.

XYZ corporation

Lighting energy savings summary

Prepare by:

Existing annual kWh:	181,828 kWh	Existing kW draw:	36.37 kW	Annual energy $$ saved:	$12,094
Proposed annual kWh:	95,234 kWh	Proposed kW draw:	18.52 kW	Estimated PRE-REBATE cost.	$13,592
Annual kWh savings:	86,594 kWh	KW savings:	17.85 kW		
% kWh savings:	47.6 %	% kW savings:	49.1 %		

Lighting inventory, recommendations, and savings

		Existing				Recommended			Savings			Estimated	
Item #	Location	Weekly hours	Qty	Fixtures	Watts/fix	Qty	Fixtures	Watts/fix	kW	Annual		Unit cost	Total cost
										kWh	Energy S		
1	Presidents office	60	8	75 Watt INC Spotlight	75	8	18 Watt CFL/SI/Ref.	18	0	1368	$219	$22	$176
2	Presidents office	60	6	2-F40T12(40W)/STD	96	6	2-F32T8(32W)/ELEC	61	0	630	$101	$48	$288
3	V.P. office	60	8	75 WATT INC Spotlight	75	8	18 Watt CFL/SI/Ref.	18	0	1,368	$219	$22	$176
4	V.P. office	60	4	2-F40T12(40W)/STD	96	4	2-F32T8(32W)/ELEC	61	0	420	$67	$48	192
5	Night lighting	168	4	2-F40T12(40W)/STD	96	4	2-F32T8(32W)/ELEC	61	0	1176	$145	$48	$192
6	Women's restroom mirror	60	12	25 Watt INC	25		None						
7	Women's restroom	60	6	2-F40T12(34W)/U/STD	94	6	2-F40T12(34W)/U/ELEC	60	0	612	$98	$48	$288
8	Men's restroom	60	6	2-F40T12(34W)/U/STD	94	6	2-F40T12(34W)/U/ELEC	60	0	612	$98	$48	$288
9	Main office area	60	56	3-F40T12(40W)/2-Class 1 11	136	56	3-F32T8(32W)/1-ELEC	90	2	7728	$1,240	$48	$2,688
10	Storage room	25	1	100 Watt INC	100	1	28 Watt PL CFL/SI	30	0	88	$19	$32	$32
11	Parking garage	168	26	100 Watt Quartz	350	26	175 Watt MH	205	3	3,166	$3,906	$200	$5,200
12	Parking garage	168	8	2-F96T12(75W)/STD	173	8	20F96T8(50W)/ELEC	104	0	4637	$572	$60	$480
13	Physical plant	80	28	2-F96T12(215W)/WHO/STD	450	28	2-F96T12(95W)/HO/ELEC	166	8	3,180	$4,741	$110	$3,080
14	Physical plant	80	162	100 Watt INC	100	16	28 Watt PL CFL/SI	30	1	4480	$668	$32	$512
	Total								1	8,659	$12,094	N/A	$13,592

FIGURE 5.4 Sample energy audit results.

Another way to perform energy audits is to use a microcomputer and a commercially available database or spreadsheet program to record the data and make the calculations. If the workload is extensive, the program can include "lookup" tables of frequently used electrical loads, utility rates, and other essential information to automate the process. We have used teams of engineers with portable computers to rapidly survey and collect the energy data from large commercial facilities. See Figure 5.4 for an example of an audit result.

Still another way of making an energy audit is to use commercially available computer software that estimates energy use for typical building occupancies based on size, type, climate zone, and other identifying parameters.

These programs are not as accurate as an actual survey, but can be used as a preliminary screening criterion to select the buildings worthy of more detailed investigations.

5.2.1.3 Identify Energy Management Opportunities

An overall estimate should be made of how effectively the facility uses its energy resources. This is difficult to do in many cases because so many operations are unique. An idea can be obtained, however, by comparing similar buildings located in similar climates. Table 5.2 shows representative values and indicates the range in performance factors that is possible.

Next, areas or equipment that use the greatest amounts of electricity should be examined. Each item should be reviewed and these questions should be asked:

- Is this actually needed?
- How can the same equipment be used more efficiently?
- How can the same purpose be accomplished with less energy?
- Can the equipment be modified to use less energy?
- Would new, more efficient equipment be cost-effective?

5.2.1.4 Implement Changes

After certain actions to save energy have been identified, an economic analysis will be necessary to establish the economic benefits, and to determine if the cost of the action is justified (refer to Chapter 3 for guidance). Those changes that satisfy the economic criteria of the building owner (or occupant) will then be implemented. Economic criteria might include a minimum return on investment (e.g., 25%), a minimum payback period (e.g., 2 years) or a minimum benefit–cost ratio (e.g., 2.0).

5.2.1.5 Monitor the Program, Establish Goals

This is the final and perhaps most important step in the program. A continuing monitoring program is necessary to ensure that energy savings do not gradually disappear as personnel return to their old ways of operation, equipment gets out of calibration, needed maintenance is neglected, etc. Also, setting goals (they should be realistic) provides energy management personnel with targets against which they can gauge their performance and the success of their programs.

TABLE 5.2 Typical Energy Use Performance Factors [EUPFs]

Type of Facility	EUPF #1		EUPF #2	
	kBTU/ft.^{2}yr	MJ/m^{2}yr	kBTU/person·yr	GJ/person·yr
Small Office Building (300 m^2)	40	455	12	12.7
Engineering Office (1,000 m^2)	30	341	14	14.8
Elementary School (4,000 m^2)	70	796	5	5.3
Office Building (50,000 m^2)	100	1,138	50	53

5.2.1.6 Summary of Energy Management Programs

The way to move forward has been outlined in two tables to provide a step-by-step procedure for electrical energy management in buildings. Table 5.3 is directed at the homeowner or apartment manager, while Table 5.4 has been prepared for the commercial building owner or operator. Industrial facilities are treated separately (refer to Chapter 10).

One problem in performing the energy audit is determining the energy used by each item of equipment. In many cases, published data are available—as in Table 5.5 for residential appliances. In other cases, engineering judgments must be made, the manufacturer consulted, or instrumentation must be provided to actually measure energy use.

TABLE 5.3 An Energy Management Plan for the Homeowner or Apartment Manager

First Step: Review Historical Data

1. Collect utility bills for a recent 12-month period.
2. Add up the bills and calculate total kWh, total $, average kWh (divide total by 12), average $, and note the months with the lowest and highest kWh.
3 Calculate a seasonal variation factor (svf) by dividing the kWh for the greatest month by the kWh for the lowest month.

Second Step: Perform Energy Audits

4. Identify all electrical loads greater than 1 kW (1000 W). Refer to Table 5 for assistance. Most electrical appliances have labels indicating the wattage. If not, use the relation $W=V\times A$.
5. Estimate the number of hours per month each appliance is used.
6. Estimate the percentage of full load (pfl) by each device under normal use. For a lamp, it is 100%; for water heaters and refrigerators, which cycle on and off, about 30%, for a range, about 25% (only rarely are *all* burners *and* the oven used), etc.
7. For each device, calculate kWh by multiplying: kW x hours/month x pfl = kWh/month.
8. Add up all kWh calculated by this method. The total should be smaller than the average monthly kWh calculated in (2).
9. Note: if the svf is greater than 1.5, the load shows strong seasonal variation, e.g., summer air conditioning, winter heating, etc. If this is the case, make two sets of calculation, one for the lowest month (when the fewest loads are operating) and one for the highest month.
10. Make a table listing the wattage of each lamp and the estimated numbers of hours of use per month for each lamp. Multiply watts times hours for each, sum, and divide by 1000. This gives kWh for the lighting loads. Add this to the total shown.
11. Add the refrigerator, television, and all other appliances or tools that use 5 kWh per month or more.
12. By this process you should now have identified 80 to 90% of electricity using loads. Other small appliances that are used infrequently can be ignored. The test is to now compare with the average month (high or low month if svf is greater than 1.5). If your total is too high, you have over estimated the pfl or the hours of use.
13. Now rank each appliance in descending order of kWh used per month. Your list should read approximately like this:

First:	Heating (in cold climates); air conditioning would be first in hot climates.
Second:	Water heating
Third:	Lighting
Fourth:	Refrigeration
Fifth:	Cooking
Sixth:	Television
Seventh to last:	All others

Third Step: Apply Energy Management Principles

14. Attack the highest priority loads first. There are three general things that can be done: (1) reduce kW (smaller lamps, more efficient appliances); (2) reduce pfl (“oven cooked” meals, change thermostats, etc.); (3) reduce hours of use (turn lights off, etc.). Refer to the text for detailed suggestions.

Fourth Step: Monitor Program, Calculate Savings

15. After the energy management program has been initiated, examine subsequent utility bills to determine if you are succeeding.
16. Calculate savings by comparing utility bills. Note: since utility rates are rising, your utility bills may not be any lower. In this case it is informative to calculate what your bill would have been without the energy management program.

TABLE 5.4 An Energy Management Plan for Commercial Building Operator

First Step: Review Historical Data

1. Collect utility bills for a recent 12-month period.
2. Add up the bills and calculate total kWh, total $, average kWh (divide total by 12), average $, and note the months with the lowest and highest kWh.
3. Calculate a seasonal variation factor (svf) by dividing the kWh for the greatest month by the kWh for the lowest month.
4. Prepare a graph of historical energy use (see Figure 5.1).

Second Step: Perform Energy Audits

5. Evaluate major loads. In commercial buildings loads can be divided into four categories:
   a) HVAC (fans, pumps, chillers, heaters, cooling towers)
   b) Lighting
   c) Office equipment and appliances (elevators, typewriters, cash registers, copy machines, hot water heaters, etc.)
   d) Process equipment (as in laundries, restaurants, bakeries, shops, etc.) Items a, b, and c are common to all commercial operations and will be discussed here. Item d overlaps with industry and the reader should also refer to Chapters 6 and 10. Generally items a, b, and d account for the greatest use of electricity and should be examined in that order.
6. In carrying out the energy audit, focus on major loads. Items that together comprise less than 1% of the total connected load in kW can often be ignored with little sacrifice in accuracy.
7. Use the methodology described above and in Chapter 4 for making the audit.
8. Compare audit results with historical energy use. If 80 to 90% of the total (according to the historical records) has been identified, this is generally adequate.

Third Step: Formulate the Energy Management Plan

9. Secure management commitment. The need for this varies with the size and complexity of the operation. However, any formal program will cost something, in terms of salary for the energy coordinator as well as (possibly) an investment in building modifications and new equipment. At this stage it is very important to project current energy usage and costs ahead for the next 3 to 5 years, make a preliminary estimate of potential savings (typically 10 to 50% per year), and establish the potential payback or return on investment in the program.
10. Develop a list of energy management opportunities (EMOs); e.g., install heat recovery equipment in building exhaust air), estimate the cost of each EMO, and also the payback. Methods for economic analysis are given in Chapter 3. For ideas and approaches useful for identifying EMO's, refer to the text.
11. Communicate the plan to employees, department heads, equipment operators, etc. Spell out who will do what, why there is a need, what are the potential benefits and savings. Make the point (if appropriate) that "the energy you save may save your job". If employees are informed, understand the purpose, and realize that the plan applies to everyone, including the President, cooperation is increased.
12. Set goals for department managers, building engineers, equipment operators, etc., and provide monthly reports so they can measure their performance.
13. Enlist the assistance of all personnel in: (1) better "housekeeping and operations", e.g., turning off lights, keeping doors closed: (2) locating obvious wastes of electricity; e.g., equipment operating needlessly, better methods of doing jobs.

Fourth Step: Implement Plan

14. Implementation should be done in two parts. First, carry out operational and housekeeping improvements with a goal of, say, 10% reduction in electricity use at essentially no cost and no reduction in quality of service or quantity of production. Second, carry out those modifications (retrofitting of buildings, new equipment, process changes) that have been shown to be economically attractive.
15. As changes are made it is important to continue to monitor electricity usage to determine if goals are being realized. Additional energy audits may be justified.

Fifth Step: Evaluate Progress, Management Report

16. Compare actual performance to the goals established in Item 12. Make corrections for weather variations, increases or decreases in production or number of employees, addition of new buildings, etc.
17. Provide a summary report of energy quantities and dollars saved, and prepare new plans for the future.

5.2.2 Electricity-Saving Techniques by Category of End Use

This section discusses strategies for saving energy that can be implemented in a short time at zero or low capital cost. Retrofit and new design strategies are then described. The ordering of topics corresponds

TABLE 5.5 Residential Energy Usage–Typical Appliances

Electric Appliances	Power (watts)	Typical Use (kWh/year)
	Home Entertainment	
Radio (solid-state)	10	10
Stereo	90	90
Color Television (solid-state)	100	229
Compact disc player	12	6
Video cassette recorder	30	15
Micro computer	125	63
Computer printer	250	25
Facsimile	65	75
	Food Preparation	
Blender	300	1
Broiler	1,140	85
Carving knife	92	8
Coffee maker	1,200	140
Deep fryer	1,448	83
Dishwasher	1,201	363
Egg cooker	516	14
Frying pan	1,196	100
Hot plate	1,200	90
Mixer	127	2
Microwave oven	1,300	170
Range		
Oven bake unit	3,200	288
Broil unit	3,600	168
Self-cleaning feature	4,000	192
Roaster	1,333	60
Sandwich grill	1,161	33
Toaster	1,146	39
Trash compactor	400	50
Waffle iron	1,200	20
Waste dispenser	445	7
	Refrigerator/Freezer	
Top freezer (18.5 to 20.4 cubic ft.) Energy star July 2001 or newer	—	444
Side-by-side (20.5 to 22.4 cubic ft.) Energy star July 2001 or newer	—	612
	Laundry	
Electric clothes dryer	—	1,020
Iron (hand)	1,100	60
Washing machine (Energy star)	—	286
Water heater	2,475	4,219
	Housewares	
Clock	2	17
Floor Polisher	305	15
Sewing machine	75	11
Vacuum cleaner	630	46
	Comfort Conditioning	
Air cleaner	50	216
Air conditioner (room)	600	600
Bed covering	177	147
Dehumidifier	257	377
Fan (attic)	370	291

(continued)

TABLE 5.5 ***(Continued)***

Electric Appliances	Power (watts)	Typical Use (kWh/year)
Fan (circulating)	88	43
Fan (roll away)	171	138
Fan (window)	200	170
Heater (portable)	1,322	176
Heating pad	65	10
Humidifier	177	163
	Health and Beauty	
Germicidal lamp	20	141
Hair dryer	1,000	40
Heat lamp (infrared)	250	13
Shaver	15	0.5
Sun lamp	279	16
Tooth brush	1.1	1.0

approximately to their importance in terms of building energy use. Energy used specifically for a process (e.g., heating) is excluded except as it relates to buildings and their occupants.

5.2.2.1 Residential HVAC

Residential HVAC units using electricity are generally heat pumps, refrigeration systems, and electrical resistance heaters. Heaters range from electric furnace types, small radiant heaters, duct heaters, and strip or baseboard heaters to embedded floor or ceiling heating systems. Efficiency for heating is usually high because there are no stack or flue losses, and the heater transfers heat directly into the living space.

Cooling systems range from window air conditioning to central refrigeration or heat pump systems. Evaporative coolers are also used in some climates.

Principal operational and maintenance strategies for existing equipment include:

- System maintenance and cleanup
- Thermostat calibration and setback
- Microprocessor controls, time clocks, night cool down
- Improved controls and operating procedures
- Heated or cooled volume reduction
- Reduction of infiltration and exfiltration losses

System maintenance is an obvious but often neglected energy-saving tool. Dirty heat transfer surfaces decrease efficiency. Clogged filters increase pressure drops and pumping power. Inoperable or malfunctioning dampers can waste energy and prevent proper operation of the system.

In residential systems, the room thermostat generally controls heating and cooling. Thermostats should be set to 24°C (75°F) or higher for cooling and approximately 18°C (65°F) during the daytime for heating. As a first step, the calibration of the thermostat should be checked because these low-cost devices can be inaccurate by as much as ±5°C. Several manufacturers now offer "smart" thermostats with microprocessor controls that can be programmed to set back or set forward the temperature depending on the time of day and day of week. By eliminating the need for manual control, they ensure that the settings will indeed be changed, whereas manual resetting of thermostats depends on occupant diligence. Some utilities have setup load control programs in which they can also communicate with smart thermostats and turn them down (or up) during high peak periods. A general rule of thumb is that for every 1°F of thermostat set back (heating) or set forward (cooling) during an 8-h period, there is a 1% savings in annual heating or cooling energy costs (the energy savings are generally lower in more severe climates).

Sometimes simple changes in controls or operating procedures will save energy. In cooling, use night air for summer cool down. When the outside air temperature is cool, turn off the refrigeration unit and circulate straight outside air. If fan units have more than one speed, use the lowest speed that provides satisfactory operation. Check the balance of the system and the operation of dampers and vents to insure that heating and cooling is provided in the correct quantities where needed.

Energy savings can be achieved by reducing the volume of the heated or cooled space. This can be accomplished by closing vents, doors, or other appropriate means. Usually it is not necessary to heat or cool an entire residence; the spare bedroom is rarely used, halls can be closed off, etc.

A major cause of energy wastage is air entering or leaving a home. Unintentional air transfer toward the inside is referred to as *infiltration*, and unintentional air transfer toward the outside is referred to as *exfiltration*. However, *infiltration* is often used to imply air leakage both into and out of a home, and this is the terminology used in this chapter. In a poorly "sealed" residence, infiltration of cold or hot air will increase heating or cooling energy use. According to Energy star, a typical home loses 25%–40% of its HVAC energy through infiltration. Infiltration also affects concentrations of indoor pollutants and can cause uncomfortable drafts. Air can infiltrate through numerous cracks and spaces created during building construction, such as those associated with electrical outlets, pipes, ducts, windows, doors, and gaps between ceilings, walls, floors, and so on. Infiltration results from temperature and pressure differences between the inside and outside of a home caused by wind, natural convection, and other forces. Major sources of air leakage are attic bypasses (paths within walls that connect conditioned spaces with the attic), fireplaces without dampers, leaky ductwork, window and door frames, and holes drilled in framing members for plumbing, electrical, and HVAC equipment. According to the U.S. DOE(Department of Energy) Energy Efficiency and Renewable Energy (EERE) program, the most significant source for infiltration is the combination of walls, ceilings, and floors that comprise 31% of the total infiltration in a typical home. Ducts (15%), fireplaces (14%), plumbing penetrations (13%), doors (11%), and windows (10%) are also substantial contributors to infiltration. Of lesser consequence are fans and vents (4%) and electrical outlets (2%).

To combat infiltration, builders of energy efficient homes use house wraps, caulking, foam insulation, tapes, and other seals. Sealing ducts in the home is also important to prevent the escape of heated or cooled air. Homeowners should also check for open doors and windows, open fireplace dampers, inadequate weather stripping around windows and doors, and any other openings that can be sealed. However, caution must be exercised to provide adequate ventilation. Standards vary, depending on the type of occupancy. Ventilation rates specified in the builder guidelines for the American Lung Association's Health House program state that for healthy homes "continuous general ventilation should be at least 1.0 cfm per 100 sq ft. of floor area plus at least 15 cfm for the first bedroom and 7.5 cfm for each additional bedroom." In addition, intermittent ventilation for the kitchen should be at least 100 cfm. For the bathrooms, rates should be 50 cfm intermittent or 20 cfm continuous. The Health House ventilation rates comply with ASHRAE standard 62.2.

In retrofit or new design projects the following techniques will save energy:

- Site selection and building orientation
- Building envelope design
- Selection of efficient heating/cooling equipment

Site selection and building orientation are not always under the control of the owner/occupant. Where possible, select a site sheltered from temperature extremes and wind. Orient the building (in cold climates) with a maximum southerly exposure to take advantage of direct solar heating in winter. Use earth berms to reduce heat losses on northerly exposed parts of the building. Deciduous trees provide summer shading but permit winter solar heating.

Building envelope design can improve heat absorption and retention in winter, and summer coolness. The first requirement is to design a well-insulated, thermally tight structure. Insulation made out of synthetic fibers reduces heating and cooling loads by resisting the transfer of heat through ceilings, walls, floors, and ducts. Reductions are usually proportionately higher for heating than for cooling because of generally larger indoor-to-outdoor temperature differences in winter than in summer. Insulation is available in bat, board, and loose-fill forms. The appropriate insulation material is selected on a basis of climate, building type, and recommended R-value. Higher R-values indicate better insulating properties. It is typically cost-effective to use greater-than-recommended R-values to improve energy efficiency above and beyond standard building practice.

Windows are an important source of heat gain and loss. The heat loss for single-pane glazing is around 5–7 $W/m^{2\circ}C$. For double glazing, the comparable value is in the range of 3–4 $W/m^{2\circ}C$, whereas for triple glazing it is 2–3 $W/m^{2\circ}C$. Window technology is constantly improving. Newer windows often have low emissivity (low-E), or spectrally selective coatings to prevent heat gain and/or loss. Low-E windows filled with argon gas have a heat loss rate of about 2 $W/m^{2\circ}C$. They have a higher visible transmittance, and are available with a low solar heat gain coefficient to reduce cooling loads in the summer. Low-E windows are available with an internal plastic film that essentially makes them triple glazed. The heat loss rate for these windows is on the order of 1 $W/m^{2\circ}C$.

Windows equipped with vinyl, wood, or fiberglass frames, or aluminum frames with a thermal barrier, provide the best insulation. It is also important to seal windows to prevent infiltration, as well as to use window coverings to minimize heat loss by radiation to the exterior during the evening. The appropriate placement of windows can also save energy by providing daylighting.

In general, the most efficient electric heating and cooling system is the heat pump. Common types are air-to-air heat pumps, either a single-package unit (similar to a window air conditioner), or a split system where the air handling equipment is inside the building and the compressor and related equipment are outdoors. Commercially available equipment demonstrates a wide range of efficiency. Heating performance is measured in terms of a heating seasonal performance factor (HSPF), in BTUs of heat added per Watt-hour of electricity input. Typical values are 6.8–9.0 and higher for the most efficient heat pumps. Cooling performance of residential heat pumps, air conditioners and packaged systems is measured in terms of a seasonal energy efficiency ratio (SEER), which describes the ratio of cooling capacity to electrical power input. Typical values are 10.0–14.5 and higher for the most efficient systems. The federal standards set in 1992 for air conditioners, heat pumps, and residential packaged units require a minimum SEER of 10.0 and a minimum HSPF of 6.8. New standards that will take effect in 2006 require a minimum SEER of 13 and a minimum HSPF of 7.7. Many existing older units have SEERs of 6–7, or roughly half the new minimum requirement. Therefore, substantial efficiency improvements are possible by replacing older equipment. In purchasing new equipment, selection of equipment with the highest HSPF and SEER should be considered. The higher initial cost of these units is almost always justified by operating savings. In addition, many utilities offer rebates for installing the more efficient units.

Sizing of equipment is important because the most efficient operation generally occurs at or near full load. Selection of oversized equipment is thus initially more expensive, and will also lead to greater operating costs.

The efficiency of heat pumps declines as the temperature difference between the heat source and heat sink decreases. Because outside air is generally the heat source, heat is most difficult to get when it is most needed. For this reason, heat pumps often have electrical backup heaters for extremely cold weather.

An alternate approach is to design the system using a heat source other than outside air. Examples include heated air (such as is exhausted from a building), a deep well (providing water at a constant year-round temperature), the ground, or a solar heat source. There are a great many variations on solar heating and heat pump combinations.

5.2.2.2 Nonresidential HVAC

HVAC systems in nonresidential installations may involve package rooftop or ground mounted units, or a central plant. Although the basic principles are similar to those discussed above in connection with residential systems, the equipment is larger and control more complex.

Efficiency of many existing HVAC systems can be improved. Modifications can reduce energy use by 10%–15%, often with building occupants unaware that changes have been made.

The basic function of HVAC systems is to heat, cool, dehumidify, humidify, and provide air mixing and ventilation. The energy required to carry out these functions depends on the building design, its duty cycle (e.g., 24 h/day use as in a hospital vs. 10 h/day in an office), the type of occupancy, the occupants' use patterns and training in the use of the HVAC system, the type of HVAC equipment installed, and finally, daily and seasonal temperature and weather conditions to which the building is exposed.

A complete discussion of psychometrics, HVAC system design, and commercially available equipment types is beyond the scope of this chapter.

Energy management strategies will be described in three parts:

- Equipment modifications (control, retrofit, and new designs)
    - Fans
    - Pumps
    - Packaged air conditioning units
    - Chillers
    - Ducts and dampers
    - Systems
- Economizer systems and enthalpy controllers
- Heat recovery techniques

5.2.2.2.1 Equipment Modifications (Control, Retrofit, and New Designs)

5.2.2.2.1.1 Fans

All HVAC systems involve some movement of air. The energy needed for this motion can make up a large portion of the total system energy used. This is especially true in moderate weather when the heating or cooling load drops off, but the distribution systems often operate at the same level.

Control. Simple control changes can save electrical energy in the operation of fans. Examples include turning off large fan systems when relatively few people are in the building, or stopping ventilation 30 min before the building closes. The types of changes that can be made will depend upon the specific facility. Some changes involve more sophisticated controls, which may already be available in the HVAC system.

Retrofit. The capacity of the building ventilation system is usually determined by the maximum cooling or heating load in the building. This load has been changing due to reduced outside air requirements, lower lighting levels, and wider acceptable comfort ranges. As a result, it is now feasible to decrease airflow in many existing commercial buildings as long as adequate indoor air quality is maintained.

The volume rate of airflow through a centrifugal fan, Q, varies directly with the speed of the impeller's rotation. This is expressed as follows for a fan whose speed is changed from N_1 to N_2:

$$Q_2 = (N_2/N_1) \times Q_1. \tag{5.1}$$

The pressure developed by the fan, P, (either static or total) varies as the square of the impeller speed:

$$P_2 = (N_2/N_1)^2 \times P_1. \tag{5.2}$$

The power needed to drive the fan, H, varies as the cube of the impeller speed:

$$H_2 = (N_2/N_1)^3 \times H_1. \tag{5.3}$$

The result of these laws is that for a given air distribution system (specified ducts, dampers, etc.), if the airflow is to be doubled, eight (2^3) times the power is needed. Conversely, if the airflow is to be cut in half, one-eighth ($\frac{1}{2}^3$) of the power is required. This is useful in HVAC systems because even a small reduction in airflow (e.g., 10%) can result in significant energy savings (27%).

The manner in which the airflow is reduced is critical in realizing these savings. Maximum savings are achieved by sizing the motor exactly to the requirements. Simply changing pulleys to provide the desired speed will also result in energy reductions according to the cubic law. The efficiency of existing fan motors tends to drop off below the half-load range.

If variable volume air delivery is required, it may be achieved through inlet vane control, outlet dampers, variable speed drives (VSDs), controlled pitch fans, or cycling. Energy efficiency in a retrofit design is best obtainable with variable speed drives on motors, or controlled pitch fans. This can be seen by calculating the power reduction that would accompany reduced flow using different methods of control, as noted below. Numbers in the table are the percent of full-flow input power:

	Fans			Pumps	
% Flow	Inlet Vanes	Dampers	VSDs	Throttle Valve	VSDs
100	102	103	102	101	103
90	86	98	76	96	77
80	73	94	58	89	58
70	64	88	43	83	41
60	56	81	31	77	30
50	50	74	22	71	19
40	46	67	15	65	13
30	41	59	9	59	8

New design. The parameters for new design are similar to those for fan retrofit. It is desirable, when possible, to use a varying ventilation rate that will decrease as the load decreases. A system such as *variable air volume* incorporates this in the interior zones of a building. In some cases, there will be a trade-off between power saved by running the fan slower and the additional power needed to generate colder air. The choices should be determined on a case-by-case basis.

5.2.2.2.1.2 Pumps

Pumps are found in a variety of HVAC applications such as chilled water, heating hot water, and condenser water loops. They are another piece of peripheral equipment that can use a large portion of HVAC energy, especially at low system loads.

Control. The control of pumps is often neglected in medium and large HVAC systems where it could significantly reduce the demand. A typical system would be a three-chiller installation where only one chiller is needed much of the year. Two chilled water pumps in parallel are designed to handle the maximum load through all three chillers. Even when only one chiller is on, both pumps are used. By manual adjustments, two chillers could be bypassed and one pump turned off. All systems should be reviewed in this manner to ensure that only the necessary pumps operate under normal load conditions.

Retrofit. Centrifugal pumps follow laws similar to fan laws, the key being the cubic relationship of power to the volume pumped through a given system. Small decreases in flow rate can save significant portions of energy.

In systems in which cooling or heating requirements have been permanently decreased, flow rates may also be reduced. A simple way to do this is by trimming the pump impeller. The pump curve must be checked first, however, because pump efficiency is a function of the impeller diameter, flow rate, and pressure rise. After trimming, one should ensure that the pump will still be operating in an efficient region. This is roughly the equivalent of changing fan pulleys in that the savings follow the cubic law of power reduction.

Another common method for decreasing flow rates is to use a "throttle" (pressure-reducing) valve. The result is equivalent to that of the discharge damper in the air-side systems. The valve creates an artificial use of energy that can be responsible for much of the work performed by the pumps. VSDs are more efficient.

New design. In a variable load situation common to most HVAC systems, more efficient systems with new designs are available, rather than the standard constant-volume pump (these may also apply to some retrofit situations).

One option is the use of several pumps of different capacities so that a smaller pump can be used when it can handle the load and a larger pump used the rest of the time. This can be a retrofit modification as well when a backup pump provides redundancy. Its impeller would be trimmed to provide the lower flow rate.

Another option is to use variable speed drive pumps. Although their initial cost is greater, they offer an improvement in efficiency over the standard pumps. The economic desirability of this or any similar change can be determined by estimating the number of hours the system will operate under various loads. Some utilities also offer rebates for installing variable speed pumps.

5.2.2.2.1.3 Package Air Conditioning Units

The most common space conditioning systems for commercial buildings are unitary equipment, either single-package systems or split systems. These are used for cooling approximately two-thirds of the air-conditioned commercial buildings in the U.S. For very large buildings or building complexes, absorption chillers or central chiller plants are used. Chillers are described in the following section.

Air conditioner efficiency is rated by one or more of three parameters: the energy efficiency ratio (EER), the SEER as described previously, and the integrated part load value (IPLV). The EER is easy to understand: it is the ratio of cooling capacity, expressed in BTU/h (kJ/h) to the power input required, in Watts. The SEER is a calculated ratio of the total annual cooling produced per annual electrical energy input in Watt-hours for units rated at less than 65,000 BTU/h. The IPLV is used for commercial loads on units rated at more than 65,000 BTU/h.

Great improvements in packaged air conditioner efficiency have been made in the last few decades, and new standards will increase efficiency even further. This is illustrated by the 30% increase in minimum SEER requirement that will take place in 2006 for split systems and single-package units under 65,000 BTU/h. As mentioned in the residential HVAC discussion earlier in the chapter, the current standard set in 1992 is a minimum SEER of 10.0 and the new standard will require a minimum SEER of 13.0. Standards for larger units (>65,000 BTU/h) will also continue to increase. As of October 29, 2001, the minimum federal standards for larger units are as follows:

	2001 Minimum Standard	
Equipment Size (BTU/h)	EER	IPLV
65,000 to <135,000	10.3	
135,000 to <240,000	9.7	
240,000 to <760,000	9.5	9.7
760,000 and larger	9.2	9.4

The Air Conditioning and Refrigeration Institute (ARI) is the basic rating agency in the U.S. In addition, there are both federal and state regulations, many of which either adopt or are similar to the ARI standards. Foreign manufacturers have similar rating systems.

Manufacturers sell systems with a broad range of efficiencies. For example, in the 65,000–135,000 BTU/h capacity range, it is possible to buy units with an EER as high as 12.5, even though the current federal standard is 10.3. Units with high EERs are typically more expensive, as the greater efficiency is achieved with larger heat exchange surface, more efficient motors, and so on.

To evaluate the economic benefit of the more efficient units, it is necessary to determine an annual operating profile that depends, in part, on the nature of the load and on the weather and temperature conditions at the site where the equipment will be installed. Or, an approximate method can be used. The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) publishes tables that show typical "equivalent full-load operating hours" for different climate zones. These can be used to estimate the savings in electrical energy use over a year, and thereby determine if the added cost of a more efficient unit is justified (it almost always is).

Because the more efficient unit is almost always more cost-effective (except in light or intermittent load conditions), one might wonder why the less efficient units are sold. The reason is that many commercial buildings are constructed and sold by developers whose principal concern is keeping the initial cost of the building as low as practicable. They do not have to bear the annual operating expense of the building after it is sold, and therefore have no incentive to minimize operating expenses.

5.2.2.2.1.4 Chillers

Chillers are often the largest single energy user in the HVAC system. The chiller cools the water used to extract heat from the building and outside ventilation air. By optimizing chiller operation the performance of the whole system is improved.

Two basic types of chillers are found in commercial and industrial applications: absorption and vapor compression (mechanical) chillers. Absorption units boil water, the refrigerant, at a low pressure through absorption into a high-concentration lithium bromide solution. Mechanical chillers cool through evaporation of a refrigerant, such as Freon, at a low pressure after it has been compressed, cooled, and passed through an expansion valve.

There are three common types of mechanical chillers. They have similar thermodynamic properties, but use different types of compressors. Reciprocating and screw-type compressors are both positive displacement units. The centrifugal chiller uses a rapidly rotating impeller to pressurize the refrigerant.

All of these chillers must reject heat to a heat sink outside the building. Some use air-cooled condensers, but most large units operate with evaporative cooling towers. Cooling towers have the advantage of rejecting heat to a lower temperature heat sink because the water approaches the ambient wet-bulb temperature, whereas air-cooled units are limited to the dry-bulb temperature. As a result, air-cooled chillers have a higher condensing temperature that lowers the efficiency of the chiller. In full-load applications, air-cooled chillers require about 1–1.3 kW, or more, per ton of cooling, whereas water-cooled chillers usually require between 0.4 and 0.9 kW per ton. Air-cooled condensers are sometimes used because they require much less maintenance than cooling towers and have lower installation costs. They can also be desirable in areas of the country where water is scarce and/or water and water treatment costs are high because they do not depend on water for cooling.

Mechanical cooling can also be performed by direct expansion (DX) units. These are similar to chillers except that they cool the air directly. They eliminate the need for chilled water pumps, and also reduce efficiency losses associated with the transfer of the heat to and from the water. DX units must be located close ($\sim$30 m) to the ducts they are cooling, so they are typically limited in size to the cooling required for a single air handler. A single large chiller can serve a number of distributed air handlers. Where the air handlers are located close together, it can be more efficient to use a DX unit.

Control. Mechanical chillers operate on a principle similar to the heat pump. The objective is to remove heat from a low-temperature building and deposit it in a higher temperature atmosphere. The lower the temperature rise that the chiller has to face, the more efficiently it will operate. It is useful, therefore, to maintain as warm a chilled water loop and as cold a condenser water loop as possible.

Energy can be saved by using lower temperature water from the cooling tower to reject the heat. However, as the condenser temperature drops, the pressure differential across the expansion valve drops, starving the evaporator of refrigerant. Many units with expansion valves, therefore, operate at a constant condensing temperature, usually 41°C (105°F), even when more cooling is available from the cooling tower. Field experience has shown that in many systems, if the chiller is not fully loaded, it can be operated with a lower cooling tower temperature.

Retrofit. Where a heat load exists and the wet-bulb temperature is low, cooling can be done directly with the cooling tower. If proper filtering is available, the cooling tower water can be piped directly into the chilled water loop. Often a direct heat exchanger between the two loops is preferred to protect the coils from fouling. Another technique is to turn off the chiller but use its refrigerant to transfer heat between the two loops. This "thermocycle" uses the same principles as a heat pipe, and only works on chillers with the proper configuration.

A low wet-bulb temperature during the night can also be utilized. It requires a chiller that handles low condensing temperatures and a cold storage tank. This thermal energy storage (TES) technique is particularly desirable for consumers with access to time-of-use electricity rates that reward peak-shaving or load-shifting.

New design. In the purchase of a new chiller, an important consideration should be the load control feature. Because the chiller will be operating at partial load most of the time, it is important that it can do so efficiently.

In addition to control of single units, it is sometimes desirable to use multiple compressor reciprocating chillers. This allows some units to be shut down at partial load. The remaining compressors operate near full load, usually more efficiently.

If a new chiller is being installed to replace an old unit, or to retire equipment that uses environmentally unacceptable chlorinated fluorocarbon (CFC) refrigerants, it is a good opportunity to install a high-efficiency chiller. The Environmental Protection Agency (EPA) lists acceptable non-CFC substitutes for various types of chillers on their website. Examples include HCFC-123, HCFC-22, HFC-134a, HFC-227ea, HFC-245fa, and ammonia.

Commonly, in commercial and industrial buildings, a convenient source of heat for a heat pump is the building exhaust air. This is a constant source of warm air available throughout the heating season. A typical heat pump design could generate hot water for space heating from this source at around 32°C–35°C (90°F–95°F). Heat pumps designed specifically to use building exhaust air can reach 66°C (150°F).

Another application of the heat pump is a continuous loop of water traveling throughout the building with small heat pumps located in each zone. Each small pump can both heat and cool, depending upon the needs of the zone. This system can be used to transfer heat from the warm side of a building to the cool side. A supplemental cooling tower and boiler are included in the loop to compensate for net heating or cooling loads.

A double bundle condenser can be used as a retrofit design for a centralized system. This creates the option of pumping the heat higher to the cooling tower or into the heating system hot duct. Some chillers can be retrofitted to act as heat pumps. Centrifugal chillers will work much more effectively with a heat source warmer than outside air (exhaust air, for example). The compression efficiency of the centrifugal chiller falls off as the evaporator temperature drops.

Because they are positive displacement machines, reciprocating and screw-type compressors operate more effectively at lower evaporator temperatures. They can be used to transfer heat across a larger temperature differential. Multistage compressors increase this capacity even further.

5.2.2.2.1.5 Ducting-Dampers

Control. In HVAC systems using dual ducts, static pressure dampers are often placed near the start of the hot or cold plenum run. They control the pressure throughout the entire distribution system and can be indicators of system operation. Often in an overdesigned system, the static pressure dampers may never open more than 25%. Fan pulleys can be changed to slow the fan and open the dampers fully, eliminating the previous pressure drop. The same volume of air is delivered with a significant drop in fan power.

Retrofit. Other HVAC systems use constant volume mixing boxes for balancing, which create their own pressure drops as the static pressure increases. An entire system of these boxes could be over pressurized by several inches of water without affecting the airflow, but the required fan power would increase (one inch of water pressure is about 250 N/m^2 or 250 Pa). These systems should be monitored to ensure that static pressure is controlled at the lowest required value. It may also be desirable to replace the constant volume mixing boxes with boxes without volume control to eliminate their minimum pressure drop of approximately 1 in. of water. In this case, static pressure dampers will be necessary in the ducting.

Leakage in any dampers can cause a loss of hot or cold air. Neoprene seals can be added to blades to slow leakage considerably. If a damper leaks more than 10% it can be less costly to replace the entire damper assembly with effective positive closing damper blades rather than to tolerate the loss of energy.

New design. In the past, small ducts were installed because of their low initial cost despite the fact that the additional fan power required offset the initial cost on a life cycle basis. ASHRAE 90.1 guidelines now set a maximum limit on the fan power that can be used for a given cooling capacity. As a result, the air system pressure drop must be low enough to permit the desired airflow. In small buildings this pressure drop is often largest across filters, coils, and registers. In large buildings the duct runs may be responsible for a significant fraction of the total static pressure drop, particularly in high velocity systems.

5.2.2.2.1.6 Systems

The use of efficient equipment is only the first step in the optimum operation of a building. Equal emphasis should be placed upon the combination of elements in a system and the control of those elements.

Control. Many systems use a combination of hot and cold to achieve moderate temperatures. Included are dual duct, multizone, and terminal reheat systems, and some induction, variable air volume and fan coil units. Whenever combined heating and cooling occurs, the temperatures of the hot and cold ducts or water loops should be brought as close together as possible, while still maintaining building comfort.

This can be accomplished in a number of ways. Hot and cold duct temperatures are often reset on the basis of the temperature of the outside air or the return air. A more complex approach is to monitor the demand for heating and cooling in each zone. For example, in a multizone building, the demand of each zone is transferred back to the supply unit by electric or pneumatic signals. At the supply end hot and cold air are mixed in proportion to this demand. The cold air temperature should be just low enough to cool the zone calling for the most cooling. If the cold air were any colder, it would be mixed with hot air to achieve the right temperature. This creates an overlap in heating and cooling not only for the zone, but also for all the zones because they would all be mixing in the colder air.

If no zone calls for total cooling, then the cold air temperature can be increased gradually until the first zone requires cooling. At this point, the minimum cooling necessary for that multizone configuration is performed. The same operation can be performed with the hot air temperature until the first zone is calling for heating only.

Note that simultaneous heating and cooling is still occurring in the rest of the zones. This is not an ideal system, but it is a first step towards improving operating efficiency.

The technique for resetting hot and cold duct temperatures can be extended to the systems that have been mentioned. It may be performed automatically with pneumatic or electric controls, or manually. In some buildings, it will require the installation of more monitoring equipment (usually only in the zones of greatest demand), but the expense should be relatively small and the payback period short.

Nighttime temperature setback is another control option that can save energy without significantly affecting the comfort level. Energy is saved by shutting off, or cycling fans. Building heat loss may also be reduced because the building is cooler and no longer pressurized.

In moderate climates complete night shutdown can be used with a morning warm-up period. In colder areas where the overall night temperature is below 4°C (40°F), it is usually necessary to provide some heat during the night. Building setback temperature is partially dictated by the capacity of the heating system to warm the building in the morning. In some cases, it may be the mean radiant temperature of the building rather than air temperature that determines occupant comfort.

Some warm-up designs use “free” heating from people and lights to help attain the last few degrees of heat. This also provides a transition period for the occupants to adjust from the colder outdoor temperatures.

In some locations during the summer, it is desirable to use night air for a cool-down period. This “free cooling” can decrease the temperature of the building mass that has accumulated heat during the day. In certain types of massive buildings (such as libraries or buildings with thick walls), a long period of night cooling may decrease the building mass temperature by a degree or two. This represents a large amount of cooling that the chiller will not have to perform the following day.

Retrofit. Retrofitting HVAC systems may be an easy or difficult task depending upon the possibility of using existing equipment in a more efficient manner. Often retrofitting involves control or ducting changes that appear relatively minor, but which greatly increase the efficiency of the system. Some of these common changes, such as decreasing airflow, are discussed elsewhere in this chapter. This section will describe a few changes appropriate to particular systems.

Both dual duct and multizone systems mix hot and cold air to achieve the proper degree of heating or cooling. In most large buildings, the need for heating interior areas is essentially nonexistent, due to internal heat generation. A modification that adjusts for this is simply shutting off air to the hot duct. The mixing box then acts as a variable air volume box, modulating cold air according to room demand as relayed by the existing thermostat (it should be confirmed that the low volume from a particular box meets minimum air requirements).

Savings from this modification come mostly from the elimination of simultaneous heating and cooling. Since fans in these systems are likely to be controlled by static pressure dampers in the duct after the fan, they do not unload very efficiently and represent only a small portion of the savings.

5.2.2.2.2 Economizer Systems and Enthalpy Controllers

The economizer cycle is a technique for introducing varying amounts of outside air to the mixed air duct. Basically it permits mixing warm return air at 24°C (75°F) with cold, outside air to maintain a preset temperature in the mixed air plenum (typically 10°C–15°C, 50°F–60°F). When the outside temperature is slightly above this set point, 100% outside air is used to provide as much of the cooling as possible. During very hot outside weather, minimum outside air will be added to the system.

A major downfall of economizer systems is poor maintenance. The failure of the motor or dampers may not cause a noticeable comfort change in the building because the system is often capable of handling the additional load. Since the problem is not readily apparent, corrective maintenance may be put off indefinitely. In the meantime, the HVAC system will be working harder than necessary for any economizer installation.

Typically, economizers are controlled by the dry-bulb temperature of the outside air, rather than its enthalpy (actual heat content). This is adequate most of the time, but can lead to unnecessary cooling of air. When enthalpy controls are used to measure wet-bulb temperatures, this cooling can be reduced. However, enthalpy controllers are more expensive and less reliable.

The rules that govern the more complex enthalpy controls for cooling-only applications are as follows:

- When outside air enthalpy is greater than that of the return air, or when outside air dry-bulb temperature is greater than that of the return air, use minimum outside air.
- When the outside air enthalpy is below the return air enthalpy, and the outside dry-bulb temperature is below the return air dry-bulb temperature but above the cooling coil control point, use 100% outside air.
- When outside air enthalpy is below the return air enthalpy and the outside air dry-bulb temperature is below the return air dry-bulb temperature and below the cooling coil controller setting, the return and outside air are mixed by modulating dampers according to the cooling set point.

These points are valid for the majority of cases. When mixed air is to be used for heating and cooling, a more intricate optimization plan will be necessary, which is based on the value of the fuels used for heating and cooling.

5.2.2.2.3 Heat Recovery

Heat recovery is often practiced in industrial processes that involve high temperatures. It can also be employed in HVAC systems.

Systems are available that operate with direct heat transfer from the exhaust air to the inlet air. These are most reasonable when there is a large volume of exhaust air, for example, in once-through systems, and when weather conditions are not moderate.

Common heat recovery systems are broken down into two types: regenerative and recuperative. Regenerative units use alternating airflow from the hot and cold stream over the same heat storage/transfer medium. This flow may be reversed by dampers, or the whole heat exchanger may rotate between streams. Recuperative units involve continuous flow; the emphasis is upon heat transfer through a medium with little storage.

The rotary regenerative unit, or heat wheel, is one of the common heat recovery devices. It contains a corrugated or woven heat storage material that gains heat in the hot stream. This material is then rotated into the cold stream where the heat is given off again. The wheels can be impregnated with a desiccant to transfer latent as well as sensible heat. Purge sections for HVAC applications can reduce carry-over from the exhaust stream to acceptable limits for most installations.

The heat transfer efficiency of heat wheels generally ranges from 60 to 85% depending upon the installation, type of media, and air velocity. For easiest installation, the intake and exhaust ducts should be located near each other.

Another system that can be employed with convenient duct location is a plate type air-to-air heat exchanger. This system is usually lighter though more voluminous than heat wheels. Heat transfer efficiency is typically in the 60%–75% range. Individual units range from 1000 to 11,000 SCFM and can be grouped together for greater capacity. Almost all designs employ counterflow heat transfer for maximum efficiency.

Another option to consider for nearly contiguous ducts is the heat pipe. This is a unit that uses a boiling refrigerant within a closed pipe to transfer heat. Since the heat of vaporization is utilized, a great deal of heat transfer can take place in a small space.

Heat pipes are often used in double-wide coils which look very much like two steam coils fastened together. The amount of heat transferred can be varied by tilting the tubes to increase or decrease the flow of liquid through capillary action. Heat pipes cannot be "turned off," so bypass ducting is often desirable. The efficiency of heat transfer ranges from 55 to 75%, depending upon the number of pipes, fins per inch, air face velocity, etc.

Runaround systems are also popular for HVAC applications, particularly when the supply and exhaust plenums are not physically close. Runaround systems involve two coils (air-to-water heat exchangers) connected by a piping loop of water or glycol solution and a small pump. The glycol solution is necessary if the air temperatures in the inlet coils are below freezing.

Standard air conditioning coils can be used for the runaround system, and some equipment manufacturers supply computer programs for size optimization. Precaution should be used when the exhaust air temperature drops below 0°C (32°F) because this can cause condensed water on the system's fins to freeze. A three-way bypass valve will maintain the temperature of the solution entering the coil at just above 0°C (32°F). The heat transfer efficiency of this system ranges from 60 to 75% depending upon the installation.

Another system similar to the runaround in layout is the desiccant spray system. Instead of using coils in the air plenums, it uses spray towers. The heat transfer fluid is a desiccant (lithium chloride) which transfers both latent and sensible heat; this is desirable in many applications. Tower capacities range from 7700 to 92,000 SCFM; multiple units can be used in large installations. The enthalpy recovery efficiency is in the range of 60%–65%.

5.2.2.2.4 Thermal Energy Storage

TES systems are used to reduce the on-peak electricity demand caused by large cooling loads. TES systems utilize several different storage media, with chilled water, ice, or eutectic salts being most common. Chilled water requires the most space, with the water typically being stored in underground tanks. Ice storage systems can be aboveground, insulated tanks with heat exchanger coils that cause the water to freeze, or can be one of several types of ice-making machines.

In a typical system, a chiller operates during off-peak hours to make ice (usually at night). Because the chiller can operate for a longer period of time than during the daily peak, it can have a smaller capacity. Efficiency is greater at night, when the condensing temperature is lower than it is during the day. During daytime operation, chilled water pumps circulate water through the ice storage system and extract heat. Systems can be designed to meet the entire load, or to meet a partial load, with an auxiliary chiller as a backup.

This system reduces peak demand and can also reduce energy use. With ice storage, it is possible to deliver water at a lower temperature than is normally done. This means that the chilled water piping can be smaller and the pumping power reduced. A low-temperature air distribution system will allow smaller ducts and lower capacity fans to deliver a given amount of cooling. Careful attention must be paid to the system design to insure occupant comfort in conditioned spaces. Some government agencies and electric utilities offer incentives to customers installing TES systems. The utility incentives could be in the form of a set rebate per ton of capacity, per kW of deferred peak demand, or a time-of-use pricing structure that favors TES.

5.2.2.3 Water Heating

5.2.2.3.1 Residential Systems

Residential water heaters typically range in size from 76 L (20 gal) to 303 L (80 gal). Electric units generally have one or two immersion heaters, each rated at 2–6 kW, depending on tank size. Energy input for water heating is a function of the temperature at which water is delivered, the supply water temperature, and standby losses from the water heater, storage tanks, and piping.

The efficiency of water heaters is referred to as the energy factor (EF). Higher EF values equate to more efficient water heaters. Typical EF values range from about 0.8–0.95 for electric resistance heaters, 0.5–0.8 for natural gas units, 0.7–0.85 for oil units, and 1.5–2.0 for heat pump water heaters.

In single-tank residential systems, major savings can be obtained by:

- Thermostat temperature setback to 60°C (140°F)
- Automated control
- Supplementary tank insulation
- Hot water piping insulation

The major source of heat loss from electric water heaters is standby losses through the tank walls and from piping because there are no flame or stack losses in electric units. The heat loss is proportional to the temperature difference between the tank and its surroundings. Thus lowering the temperature to 60°C will result in two savings: (1) a reduction in the energy needed to heat water, and (2) a reduction in the amount of heat lost. Residential hot water uses do not require temperatures in excess of 60°C; for any special use which does, it would be advantageous to provide a booster heater to meet this requirement when needed, rather than maintain 100–200 L of water continuously at this temperature with associated losses.

When the tank is charged with cold water, both heating elements operate until the temperature reaches a set point. After this initial rise, one heating element thermostatically cycles on and off to maintain the temperature, replacing heat that is removed by withdrawing hot water, or that is lost by conduction and convection during standby operation.

Experiments indicate that the heating elements may be energized only 10%–20% of the time, depending on the ambient temperature, demand for hot water, water supply temperature, etc. By carefully scheduling hot water usage, this time can be greatly reduced. In one case, a residential water heater was operated for 1 h in the morning and 1 h in the evening. The morning cycle provided sufficient hot water for clothes washing, dishes, and other needs. Throughout the day the water in the tank, although gradually cooling, was still sufficiently hot for incidental needs. The evening heating cycle provided sufficient water for cooking, washing dishes, and bathing. Standby losses were reduced. Electricity use was cut to a fraction of the normal amount.

This method requires the installation of a time clock or other type of control to regulate the water heater. A manual override can be provided to meet special needs.

Supplementary tank insulation can be installed at a low cost to reduce standby losses. The economic benefit depends on the price of electricity and the type of insulation installed. However, paybacks of a few months up to a year are typical on older water heaters. Newer units have better insulation and reduced losses. Hot water piping should also be insulated, particularly when hot water tanks are located outside or when there are long piping runs. If copper pipe is used, it is particularly important to insulate the pipe for the first 3–5 m where it joins the tank because it can provide an efficient heat conduction path.

Because the energy input depends on the water flow rate and the temperature difference between the supply water temperature and the hot water discharge temperature, reducing either of these two quantities reduces energy use. Hot water demand can be reduced by cold water clothes washing, and by providing hot water at or near the use temperature, so as to avoid the need for dilution with cold water. Supply water should be provided at the warmest temperature possible. Because reservoirs and underground piping systems are generally warmer than the air temperature on a winter day in a cold climate, supply piping should be buried, insulated, or otherwise kept above the ambient temperature.

Solar systems are available today for heating hot water. Simple inexpensive systems can preheat the water, reducing the amount of electricity needed to reach the final temperature. Alternatively, solar heaters (some with electric backup heaters) are also available, although initial costs may be prohibitively high depending on the particular installation.

Heat pump water heaters may save as much as 25%–30% of the electricity used by a conventional electric water heater. Some utilities have offered rebates of several thousand dollars to encourage customers to install heat pump water heaters.

Tankless water heaters, also called *on-demand* or *instantaneous* water heaters, have been used for decades in Asia, Europe, and South America, but only recently have become common in the United States. Both electric and gas versions are available. The basic operating principal is that the flow of water actuates the gas-fired or electric heating element. A microcomputer senses water flow rate and temperature and controls the heat input accordingly. There are two key advantages. First, standby losses are virtually eliminated because the unit only produces hot water when it is required. Second, the units are very compact and require a fraction of the space required by tank-type water heaters. Efficiencies (EF) are in the range of 0.80–0.82 for gas units and around 0.95 for electric units. For gas units, if equipped with an electric igniter, the pilot light losses are also eliminated. The larger units match the performance of tank-type water heaters. Tests performed by the authors in Southern California show that hot water supply is adequate for a typical three- or four-bedroom residence.

The microwave water heater is another interesting technology that is just beginning to emerge in both residential and commercial applications. Microwave water heaters are also tankless systems that produce hot water only when needed, thereby avoiding the energy losses incurred by conventional water heaters during the storage of hot water. These heaters consist of a closed, stainless steel chamber with a silica-based flexible coil and a magnetron. When there is a demand for hot water, either because a user has opened a tap or because of a heater timing device, water flows into the coil and the magnetron bombards it with microwave energy at a frequency of 2450 MHz. The microwave energy excites the water molecules, heating the water to the required temperature.

Heat recovery is another technique for preheating or heating water, although opportunities in residences are limited. This is discussed in more detail under commercial water heating.

Apartments and larger buildings use a combined water heater/storage tank, a circulation loop, and a circulating pump. Cold water is supplied to the tank, which thermostatically maintains a preset temperature, typically 71°C (160°F). The circulating pump maintains a flow of water through the circulating loop, so hot water is always available instantaneously upon demand to any user. This method is also used in hotels, office buildings, etc.

Adequate piping and tank insulation is even more important here because the systems are larger and operate at higher temperature. The circulating hot water line should be very well insulated. Otherwise, it will dissipate heat continuously.

5.2.2.3.2 Heat Recovery in Nonresidential Systems

Commercial/industrial hot water systems offer many opportunities for employing heat recovery. Examples of possible sources of heat include air compressors, chillers, heat pumps, refrigeration systems, and water-cooled equipment. Heat recovery permits a double energy savings in many cases. First, recovery of heat for hot water or space heating reduces the direct energy input needed for heating. The secondary benefit comes from reducing the energy used to dissipate waste heat to a heat sink (usually the atmosphere). This includes using energy and energy expended to operate cooling towers and heat exchangers.

Solar hot water systems are also finding increasing use. Interestingly, the prerequisites for solar hot water systems also permit heat recovery. After the hot water storage capacity and backup heating capability has been provided for the solar hot water system, it is economical to tie in other sources of waste heat (e.g., water jackets on air compressors).

5.2.2.4 Lighting

There are seven basic techniques for improving the efficiency of lighting systems:

- Delamping
- Relamping
- Improved controls
- More efficient lamps and devices
- Task-oriented lighting
- Increased use of daylight
- Room color changes, lamp maintenance

The first two techniques and possibly the third are low cost and may be considered operational changes. The last four items generally involve retrofit or new designs.

The first step in reviewing lighting electricity use is to perform a lighting survey. An inexpensive handheld light meter can be used as a first approximation; however, distinction must be made between raw intensities (lux or foot-candles) and illumination quality recorded in this way.

Many variables can affect the “correct” lighting values for a particular task: task complexity, age of employee, glare, etc. For reliable results, consult a lighting specialist, or refer to the literature and publications of the Illuminating Engineering Society.

The lighting survey indicates those areas of the building where lighting is potentially inadequate or excessive. Deviations from illumination levels that are adequate can occur for several reasons: over design, building changes, change of occupancy, modified layout of equipment or personnel, more efficient lamps, improper use of equipment, dirt buildup, etc.

After the building manager has identified areas with potentially excessive illumination levels, he or she can apply one or more of the seven techniques previously listed. Each of these will be described briefly.

Delamping refers to the removal of lamps to reduce illumination to acceptable levels. With incandescent lamps, bulbs are removed. With fluorescent or high intensity discharge lamps, ballasts account for 10%–20% of total energy use and should be disconnected after lamps are removed. However, delamping often changes the distribution of the lighting, as well as the overall level, and is therefore generally not recommended.

Relamping refers to the replacement of existing lamps with lamps of lower wattage or increased efficiency. Low wattage fluorescent tubes that require 15%–20% less wattage, but produce 10–15% less light, are available. In Chapter 7, Energy Efficient Lighting Technologies, there is a discussion on the idea of using lower-power-factor electronic ballasts, as well as further details on energy efficient lighting technologies. In some types of high-intensity discharge (HID) lamps, a more efficient lamp can be substituted directly (it too will have a lower lumen output). However, in most cases, ballasts must also be changed.

Improved controls permit lamps to be used only when and where needed. For example, certain office buildings have all lights for one floor on a single contactor. These lamps will be switched on at 6:00 a.m. before work begins, and are not turned off until 10:00 p.m. when maintenance personnel finish their cleanup duties.

Energy usage can be cut by as much as 50% by installing individual switches for each office or work area, installing timers, occupancy sensors, photocell controls, and/or dimmers, or by instructing custodial crews to turn lights on as needed and turn them off when work is complete. Sophisticated building-wide lighting control systems are also available, and are being implemented at an increasing rate, particularly in commercial buildings.

There is a great variation in the efficacy (a measure of light output per unit of electricity input) of various lamps. Incandescent lamps have the lowest efficacy, typically 5–20 lm/W. Wherever possible, fluorescent lamps should be substituted for incandescent lamps. This not only saves energy, but offers substantial economic savings as well because fluorescent lamps last 10–50 times longer. Conventional fluorescent lamps have efficacies in the range of 30–70 lm/W; high-efficiency fluorescent systems currently yield about 85–100 lm/W.

Compact fluorescent lamps can also be used as substitutes for a wide range of incandescent lamps. They are available in wattages of 5–70 W and will replace incandescent lamps with about one-fourth of the energy consumption. In addition to the energy savings, they have a 10,000-h rated life, and thus do not need to be replaced as often as incandescent lamps.

Still greater improvements are possible with HID lamps such as metal halide and high-pressure sodium lamps. Although they are generally not suited to residential use (high light output and high capital cost), they are increasingly being used in commercial and industrial buildings for their high efficiency and long life. It should be noted that HID lamps are not suited for any area where lamp switching is required, as they still take several minutes to restart after being switched off.

Improving ballasts is another way of saving lighting energy. One example of a significant increase in efficacy in the commercial sector is illustrated in the transition from T12 (1.5-in. diameter) fluorescent lamps with magnetic ballasts to T8 (1-in. diameter) fluorescent lamps with electronic ballasts. This transition began to occur in the late 1970s and early 1980s. Now T8 electronic ballast systems are the standard for new construction and retrofits (note that competition from new T5 systems is increasing). The efficacy improvement, depending on the fixture, is roughly 20%–40%, or even more. For example, a two-lamp F34T12 fixture (a fixture with two 1.5-in. diameter, 34-W lamps) with energy-saving magnetic ballast requires 76 W, whereas a two-lamp F32T8 fixture (a fixture with two 1-in. diameter, 32-W lamps) with electronic ballast requires only 59 W, which is an electricity savings of 22%. The savings is attributable to the lower wattage lamps as well as the considerably more efficient ballast.

In addition to the lighting energy savings, there are additional savings from the reduced air conditioning load due to less heat output from the ballasts.

Task-oriented lighting is another important lighting concept. In this approach, lighting is provided for work areas in proportion to the needs of the task. Hallways, storage areas, and other nonwork areas receive less illumination. Task lighting can replace the so-called “uniform illumination” method sometimes used in office buildings. The rationale for uniform illumination was based on the fact that the designer could never know the exact layout of desks and equipment in advance, so uniform illumination was provided. This also accommodates revisions in the floor plan. Originally, electricity was cheap and any added cost was inconsequential.

Daylighting was an important element of building design for centuries before the discovery of electricity. In certain types of buildings and operations today, daylighting can be utilized to at least reduce (if not replace) electric lighting. Techniques include windows, an atrium, skylights, etc. There are obvious limitations, such as those imposed by the need for privacy, 24-h operation, and building core locations with no access to natural light.

The final step is to review building and room color schemes and decor. The use of light colors can substantially enhance illumination without modifying existing lamps.

An effective lamp maintenance program also has important benefits. Light output gradually decreases over lamp lifetime. This should be considered in the initial design and when deciding on lamp replacement. Dirt can substantially reduce light output; simply cleaning lamps and luminaries more frequently can gain up to 5%–10% greater illumination, permitting some lamps to be removed.

5.2.2.5 Refrigeration

The refrigerator, at roughly 40–140 kWh/month depending on the size and age of the model, is among the top six residential users of electricity. In the last 50 years, the design of refrigerator/freezers has changed considerably, with sizes increasing from 5–10 to 20–25 ft.^{3} today. At the same time, the energy input per unit increased up until the oil embargo, after which efforts were made that led to a steady decline in energy use per unit between the mid-1970s through today, despite increases in average refrigerator size. The net result is that current refrigerators use about as much energy as those half their size did 40 years ago.

Energy losses in refrigerators arise from a variety of sources. The largest losses are due to heat gains through the walls and door openings. Because much of the energy used by a refrigerator depends on its design, care should be used in selection. Look for Energy star models to maximize efficiency.

Purchase of a new, more efficient unit is not a viable option for many individuals who have a serviceable unit and do not wish to replace it. In this case, the energy management challenge is to obtain the most effective operation of the existing equipment.

More efficient operation of refrigeration equipment can be achieved by:

- Better insulation (although this is not generally a user option for refrigerators)
- Disconnecting or reducing operation of automatic defrost and anti-sweat heaters
- Providing a cool location for the refrigerator coils (or reduce room temperature); also clean coils frequently
- Reducing the number of door openings
- Increasing temperature settings
- Precooling foods before refrigerating

Commercial refrigeration systems are found in supermarkets, liquor stores, restaurants, hospitals, hotels, schools, and other institutions—about one-fifth of all commercial facilities. Systems include walk-in dairy cases, open refrigerated cases, and freezer cases. In a typical supermarket, lighting, HVAC, and miscellaneous uses account for half the electricity use, while refrigerated display cases, compressors, and condenser fans account for the other half. Thus commercial refrigeration can be an important element of electric energy efficiency.

It is common practice in some types of units to have the compressor and heat exchange equipment located remotely from the refrigerator compartment. In such systems, a cool location should be selected, rater than locating the compressor next to other equipment which gives off heat. Many of the newer commercial refrigerators now come equipped with heat recovery systems, which recover compressor heat for space conditioning or water heating.

Walk-in freezers and refrigerators lose energy though door openings; refrigerated display cases have direct transfer of heat. Covers, strip curtains, air curtains, glass doors, or other thermal barriers can help mitigate these problems. The most efficient light sources should be used in large refrigerators and freezers; every 1 W eliminated saves 3 W. Elimination of 1 W of electricity to produce light also eliminates an additional 2 W required to extract the heat. Other improvements can reduce energy use, including high-efficiency motors, variable speed drives, more efficient compressors, and improved refrigeration cycles and controls.

5.2.2.6 Cooking

Cooking accounted for about 7% of residential electricity use in 2001 and about 2.1% of commercial electricity use in 1999. Since the last edition of this handbook, consumer behavior toward cooking has changed. Consumers today are cooking less in the home and dining out or picking up prepared food more often. Figure 5.5 compares the number of hot meals cooked in the home during the years of 1993 and 2001. The data show that fewer households cooked one or more hot meals per day in 2001 than in 1993; in addition, more households cooked a few meals or less per week in 2001 than in 1993. Consumers are also purchasing more foods that are easier to prepare—convenience is key to the modern family. In response, the food processing industry offers a wide variety of pre-prepared, ready-to-eat products.

Though habits are changing and more cooking is occurring outside the home (in restaurants and food processing facilities), reductions in energy use are still important. In general, improvements in energy use efficiency for cooking can be divided into three categories:

- More efficient use of existing appliances
- Use of most efficient existing appliances
- More efficient new appliances

The most efficient use of existing appliances can lead to substantial reductions in energy use. Although slanted towards electric ranges and appliances, the following observations also apply to cooking devices using other sources of heat.

First, select the right size equipment for the job. Do not heat excessive masses or large surface areas that will needlessly radiate heat. Second, optimize heat transfer by ensuring that pots and pans provide good thermal coupling to the heat sources. Flat-bottomed pans should be used on electric ranges. Third, be sure that pans are covered to prevent heat loss and to shorten cooking times. Fourth, when using the oven, plan meals so several dishes are cooked at once. Use small appliances (electric fry pans, "slow" cookers, toaster ovens, etc.) whenever they can be substituted efficiently for the larger appliances such as the oven.

Different appliances perform similar cooking tasks with widely varying efficiencies. For example, the electricity used and cooking time required for common food items can vary as much as ten to one in energy use and five to one in cooking times, depending on the method. As an example, four baked potatoes require 2.3 kWh and 60 min in an oven (5.2 kW) of an electric range, 0.5 kWh and 75 min in a

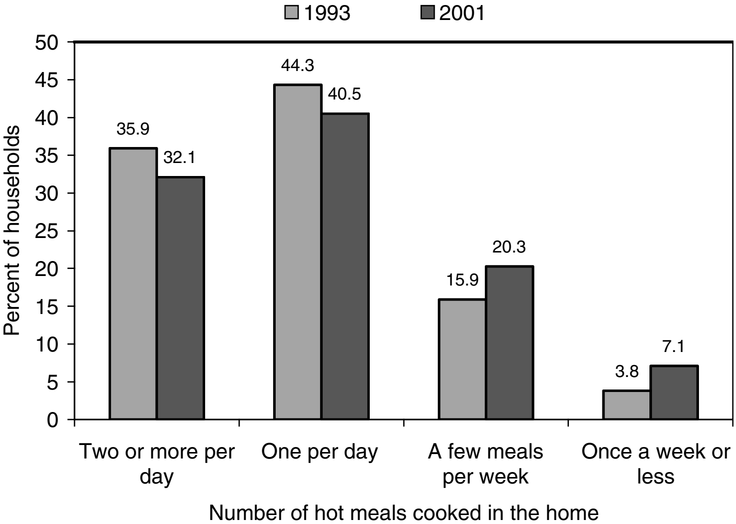

FIGURE 5.5 Number of hot meals cooked in the home for all U.S. households, 1993 and 2001.

toaster oven (1.0 kW), or 0.3 kWh and 16 min in a microwave oven (1.3 kW). Small appliances are generally more efficient when used as intended. Measurements in a home indicated that a pop-up toaster cooks two slices of bread using only 0.025 kWh. The toaster would be more efficient than using the broiler in the electric range oven, unless a large number of slices of bread (more than 17 in this case) were to be toasted at once.

Cooking several dishes at once can save energy. A complete meal, consisting of a ham (2.3 kg), frozen peas (0.23 kg), four yams, and a pineapple upside-down cake (23×23 cm^2) were cooked separately using a toaster oven and an electric range, together in an electric oven, and separately in a microwave oven. Cooked separately using the toaster oven and range required 5.2 kWh; together in the oven took 2.5 kWh, whereas the microwave required 1.2 kWh.

If new appliances are being purchased, select the most efficient ones available. Heat losses from a conventional oven approach 1 kW, with insulation accounting for about 50%; losses around the oven door edge and through the window are next in importance. These losses are reduced in certain models. Self-cleaning ovens are normally manufactured with more insulation. Careful design of heating elements can also contribute to better heat transfer. Typically, household electric ranges require around 3200 W for oven use, 3600 W for broiler use, and 4000 W for use of the self-cleaning feature.

Microwave cooking is highly efficient for many types of foods because the microwave energy is deposited directly in the food. Energy input is minimized because there is no need to heat the cooking utensil. Although many common foods can be prepared effectively using a microwave oven, different methods must be used, as certain foods are not suitable for microwave cooking. A typical microwave oven requires about 1300 W. Convection ovens and induction cook tops are two newer developments that may also reduce cooking energy use.

Commercial cooking operations range from small restaurants and cafes, where methods similar to those described above for residences are practiced, to large institutional kitchens in hotels, hospitals, and finally, to food processing plants.

Many of the same techniques apply. Microwave heating is finding increasing use in hotel and restaurant cooking. Careful scheduling of equipment use, and provision of several small units rather than a single large one, will save energy. For example, in restaurants, grills, soup kettles, bread warmers, etc., often operate continuously. Generally it is unnecessary to have full capacity during off-peak hours; one small grill might handle mid-morning and mid-afternoon needs, permitting the second and third units to be shut down. The same strategy can be applied to coffee warming stations, hot plates, etc.

In food processing plants where food is cooked and canned, heat recovery is an important technique. Normally, heat is rejected via cooling water at some step in the process. This heat can be recovered and used to preheat products entering the process, decreasing the amount of heating that eventually must be done.

5.2.2.7 Residential Appliances

A complete discussion of energy management opportunities associated with all the appliances found in homes is beyond the scope of this chapter. However, several of the major ones will be discussed and general suggestions applicable to the others will be given.

5.2.2.7.1 Clothes Drying

Clothes dryers typically use about 2.5 kWh per load. A parameter called the *energy factor*, which is a measure of the pounds of clothing dried per kWh of electricity consumed, can be used to quantify the efficiency of clothes drying. The minimum EF for a standard capacity electric dryer is 3.01. In the U.S., new dryers are not required to display energy use information, so it is difficult to compare models. In fact, most electric dryers on the market are comparable in their construction and the basic heating technology. However, the actual energy consumption of the dryer varies with the types of controls it has, and how the operator uses those controls. Models with moisture-sensing capability can result in the most energy savings—savings on the order of 15% compared to conventional operation are common.

In addition, electric clothes dryers operate most efficiently when fully loaded. Operating with one-third to one-half load costs roughly 10%–15% in energy efficiency.

Locating clothes dryers in heated spaces could save 10%–20% of the energy used by reducing energy needed for heating up. Another approach is to save up loads and do several loads sequentially, so the dryer does not cool down between loads.

The heavier the clothes the greater the amount of water they hold. Mechanical water removal (pressing, spinning, wringing) generally requires less energy than electric heat. Therefore, be certain the washing machine goes through a complete spin cycle (0.1 kWh) before putting clothes in the dryer.

Solar drying, which requires a clothesline (rope) and two poles or trees, has been practiced for millennia and is very sparing of electricity. The chief limitation is, of course, inclement weather. New technologies such as microwave or heat pump clothes dryers may help reduce clothes drying energy consumption in the future.

5.2.2.7.2 Clothes Washing

The modified energy factor (MEF) can be used to compare different models of clothes washers. It is a measure of the machine energy required during washing, the water heating energy, and the dryer energy needed to remove the remaining moisture. A higher MEF value indicates a more efficient clothes washer. All new clothes washers manufactured or imported after January 1, 2004 are required to have an MEF of at least 1.04, and after January 1, 2007, an MEF of at least 1.26. In addition, as of January 2004, a minimum MEF of 1.42 is required for a clothes dryer to be qualified as an Energy star unit. A typical Energy star unit uses about 0.7 kWh per load.

Electric clothes washers are designed for typical loads of 3–7 kg. Surprisingly, most of the energy used in clothes washing is for hot water; the washer itself only requires a few percent of the total energy input. Therefore, the major opportunity for energy management in clothes washing is the use of cold or warm water for washing. Under normal household conditions it is not necessary to use hot water. Clothes are just as clean (in terms of bacteria count) after a 20°C wash as after a 50°C wash. If there is concern for sanitation (e.g., a sick person in the house), authorities recommend use of chlorine bleach. If special cleaning is required, such as removing oil or grease stains, hot water (50°C) and detergent will emulsify oil and fat. There is no benefit in a hot rinse.

A secondary savings can come from using full loads. Surveys indicate that machines are frequently operated with partial loads, even though a full load of hot water is used.

5.2.2.7.3 Dishwashers

The two major energy uses in electric dishwashers are the hot water and the dry cycle. Depending on the efficiency of the model and operation, dishwashers use between 2 and 5 kWh per load.

The water heating often accounts for 80% of the total energy requirement of a dishwasher. The volume of hot water used ranges from about 5 gal for the more efficient units to more than double that for less efficient models. The water volume can be varied on some machines depending on the load.

Some models also allow for a no-heat drying option. If not available, stop the cycle prior to the drying step and let the dishes air-dry. Operating the dishwasher with a full load and using a cold water prerinse are additional ways to minimize energy use.

5.2.2.7.4 General Suggestions for Residential Appliances and Electrical Equipment

Many electrical appliances (pool pumps, televisions, stereos, DVD and CD players, electronic gaming systems, aquariums, blenders, floor polishers, hand tools, mixers, etc.) perform unique functions that are difficult to duplicate. This is their chief value.

Attention should be focused on those appliances that use more than a few percent of annual electricity use. General techniques for energy management include:

- Reduce use of equipment where feasible (e.g., turn off entertainment systems when not in use)
- Perform maintenance to improve efficiency (e.g., clean pool filters to reduce pumping power)
- Schedule use for off-peak hours (evenings)

The last point requires further comment and applies to large electric appliances such as washers, dryers, and dishwashers. Some utilities now offer "time-of-use" rates that include a premium charge for usage occurring "on-peak" (when the greatest demand for electricity takes place), and lower energy costs for "off-peak" electricity use. By scheduling energy-intensive activities for off-peak hours (clothes washing and drying in the evening for example) the user helps the utility reduce its peaking power requirement, thereby reducing generating costs. The utility then returns the favor by providing lower rates for off-peak use.

5.2.2.8 Computers and Office Equipment

Computers are fairly ubiquitous in both the residential and commercial sectors at this point. There are significant energy savings available from going to LCD displays in place of CRT displays, and in enabling the sleep or power saver routines available with the machines. The use of laptop machines in place of desktop machines also offers substantial savings.

A wide variety of equipment in addition to computers can be found in commercial buildings, depending on the size and function. Process equipment within buildings (e.g., clothes washers in laundries, printing presses, refrigerated display cases, etc.) will not be discussed due to the great diversity of these items.

Excluding process equipment, major energy-using equipment in commercial buildings generally includes HVAC systems, lighting, and "other" equipment. Because energy management options for HVAC and lighting have already been described, the discussion here will be directed at "other" equipment, including:

- Computers, local area networks and peripherals
- Facsimile machines, electronic mail
- Vending machines and water coolers
- Copy machines
- Elevators and escalators

The energy management opportunities with these types of equipment are more restricted. One obvious strategy is to insure that all equipment is turned off when not needed or not in use. Another is to size equipment with the right capacity to do the job, avoiding overcapacity, which increases both energy and demand charges.

In general, the most likely opportunity with elevators, escalators, and similar equipment is to shut them down during off hours or other times when they are not needed.

There is a host of miscellaneous equipment in buildings that contributes only a small percentage of total energy use, is used infrequently, and is an unlikely candidate for improved efficiency.

5.3 Closing Remarks

This chapter has discussed the management of electrical energy in buildings. Beginning with a discussion of energy use in buildings, next outlined was the major energy-using systems and equipment, along with a brief description of their particular features that influence energy use and waste. A systematic methodology for implementing an energy management program was then described. The procedure has been implemented in a wide variety of situations including individual homes, commercial buildings, institutions, multinational conglomerates, and cities, and has worked well in each case. Following the discussion of how to set up an energy management program, a series of techniques for saving electricity in each major end use was discussed. The emphasis has been on currently available, cost-effective technology. Undoubtedly, there are other techniques available, but this chapter has concentrated on those that are known to work in today's economy for the typical energy consumer.

The first edition of this book was published in 1980. Much of the data in the first edition dated from the 1975–1980 timeframe, when the initial response to the oil embargo of 1973 was gathering momentum and maturing. It is remarkable to return to those data and look at the progress that has been made. In 1975, total U.S. energy use was 71.2 quads (75.1 GJ). Most projections at that time predicted U.S. energy use in excess of 100 quads (106 GJ) by 1992; instead, it only reached 85 quads (90 GJ) by 1992. In fact, by 2004, total U.S. energy use was close, but still had not reached the 100 quad mark; the preliminary estimate was 99.7 quads (105 GJ). During this same period, U.S. gross domestic product (GDP) increased from $4.31 trillion (1975) to $7.34 trillion (1992) to $10.8 trillion (2004). In other words, energy usage increased by 40% while enabling GDP to increase 2.5-fold. Some of this is due to a decrease in domestic energy-intensive industry, but for the most part it represents a remarkable improvement in overall energy efficiency.

As noted earlier in this chapter, a significant growth of the residential sector has occurred in the intervening decades, but efficiency improvements have held down the growth rate of energy consumption. The improvement in energy efficiency in lighting, refrigerators, air conditioning, and other devices has been truly remarkable. Today, the local hardware or homebuilder's store has supplies of energy efficient devices that were beyond imagination in 1973.

This is a remarkable accomplishment, technically and politically, given the diversity of the residential/commercial market. Besides the huge economic savings this has meant to millions of homeowners, apartment dwellers, and businesses, think of the environmental benefits associated with avoiding the massive additional amounts of fuel, mining, and combustion which otherwise would have been necessary.

6

Heating, Ventilating, and Air Conditioning Control Systems

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6.1 Introduction

This chapter describes the essentials of control systems for heating, ventilating, and air conditioning (HVAC) of buildings designed for energy conserving operation. Of course, there are other renewable and energy conserving systems that require control. The principles described herein for buildings also apply with appropriate and obvious modification to these other systems. For further reference, the reader is referred to several standard references in the list at the end of this chapter.

HVAC system controls are the information link between varying energy demands on a building's primary and secondary systems and the (usually) approximately uniform demands for indoor environmental conditions. Without a properly functioning control system, the most expensive, most thoroughly designed HVAC system will be a failure. It simply will not control indoor conditions to provide comfort.

The HVAC designer must design a control system that

- Sustains a comfortable building interior environment
- Maintains acceptable indoor air quality
- Is as simple and inexpensive as possible and yet meets HVAC system operation criteria reliably for the system lifetime
- Results in efficient HVAC system operation under all conditions
- Commissions the building, equipment and control systems
- Documents the system operation so that the building staff can successfully operate and maintain the HVAC system

It is a considerable challenge for the HVAC system designer to design a control system that is energy efficient and reliable. Inadequate control system design, inadequate commissioning, and inadequate documentation and training for the building staff often create problems and poor operational control of HVAC systems. This chapter describes the basics of HVAC control and the operational needs for successfully maintained operation. The reader is encouraged to review the following references on the subject: ASHRAE (2002, 2003, 2004, 2005), Haines (1987), Honeywell (1988), Levine (1996), Sauer, Howell, and Coad (2001), Stein and Reynolds (2000), and Tao and Janis (2005).

To achieve proper control based on the control system design, the HVAC system must be designed correctly and then constructed, calibrated and commissioned according to the mechanical and electrical systems drawings. These must include properly sized primary and secondary systems. In addition, air stratification must be avoided, proper provision for control sensors is required, freeze protection is necessary in cold climates, and proper attention must be paid to minimizing energy consumption, subject to reliable operation and occupant comfort.

The principle and final controlled variable in buildings is zone temperature (and to a lesser extent humidity and/or air quality in some buildings). This chapter will therefore focus on methods to control temperature. Supporting the zone temperature control, numerous other control loops exist in buildings within the primary and secondary HVAC systems, including boiler and chiller control, pump and fan control, liquid and air flow control, humidity control, and auxiliary system control (for example, thermal energy storage control). This chapter discusses only automatic control of these subsystems. Honeywell (1988) defines an automatic control system as "a system that reacts to a change or imbalance in the variable it controls by adjusting other variables to restore the system to the desired balance."

Figure 6.1 defines a familiar control problem with feedback. The water level in the tank must be maintained under varying outflow conditions. The float operates a valve that admits water to the tank as the tank is drained. This simple system includes all the elements of a control system:

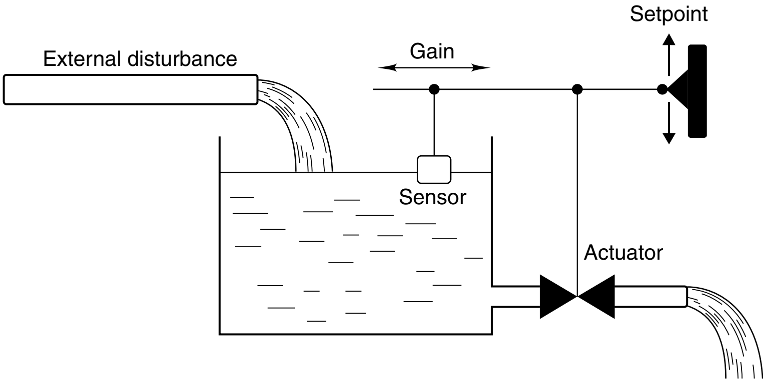

FIGURE 6.1 Simple water level controller. The setpoint is the full water level; the error is the difference between the full level and the actual level.

- Sensor—float; reads the controlled variable, the water level
- Controller—linkage connecting float to valve stem; senses difference between full tank level and operating level and determines needed position of valve stem
- Actuator (controlled device)—internal valve mechanism; sets valve (the final control element) flow in response to level difference sensed by controller
- Controlled system characteristic—water level; this is often termed the controlled variable

This system is called a *closed loop* or *feedback* system because the sensor (float) is directly affected by the action of the controlled device (valve). In an open loop system the sensor operating the controller does not directly sense the action of the controller or actuator. An example would be a method of controlling the valve based on an external parameter such as time of day, which may have an indirect relation to water consumption from the tank.

There are four common methods of control, of which Figure 6.1 shows but one. In the next section, each method will be described in relation to an HVAC system example.

6.2 Modes of Feedback Control

Feedback control systems adjust an output control signal based on feedback. The feedback is used to generate an error signal, which then drives a control element. Figure 6.1 illustrates a basic control system with feedback. Both off–on (two-position) control and analog (variable) control can be used. Numerous methodologies have been developed to implement analog control. These include proportional, proportional-integral (PI), proportional-integral-differential (PID), fuzzy logic, neural networks, and auto-regressive moving average (ARMA) control systems. Proportional and PI control systems are used for most HVAC control applications.

Figure 6.2a shows a steam coil used to heat air in a duct. The simple control system shown includes an air temperature sensor, a controller that compares the sensed temperature to the setpoint, a steam valve controlled by the controller, and the coil itself. This example system will be used as the point of reference when discussing the various control system types. Figure 6.2b is the control diagram corresponding to the physical system shown in Figure 6.2a.

Two-position control applies to an actuator that is either fully open or fully closed. In Figure 6.2a, the valve is a two-position valve if two-position control is used. The position of the steam valve is determined by the value of the coil outlet temperature. Figure 6.3 depicts two-position control of the valve. If the air temperature drops below 95°F, the valve opens and remains open until the air temperature reaches 100°F. The differential is usually adjustable, as is the temperature setting itself. Two-position control is the least expensive method of automatic control and is suitable for control of HVAC systems with large time constants. Examples include residential space and water heating systems. Systems that are fast-reacting should not be controlled using this approach because overshoot and undershoot may be excessive.

Proportional control adjusts the controlled variable in proportion to the difference between the controlled variable and the setpoint. For example, a proportional controller would increase the coil heat rate in Figure 6.2 by 10% if the coil outlet air temperature dropped by an amount equal to 10% of the temperature range specified for the heating to go from off to fully on. Equation 6.1 defines the behavior of a proportional control loop:

$$T = T_{\text{set}} + K_{\text{p}}e \tag{6.1}$$

where T is the controller output, T_{set} is the set temperature corresponding to a constant value of controller output when no error exists, K_{p} is the loop gain that determines the rate or proportion at which the control signal changes in response to the error, and e is the error. In the case of the steam coil, the error is the difference between the air temperature setpoint and the sensed supply air temperature:

$$e = T_{\text{set}} - T_{\text{sa}} \tag{6.2}$$

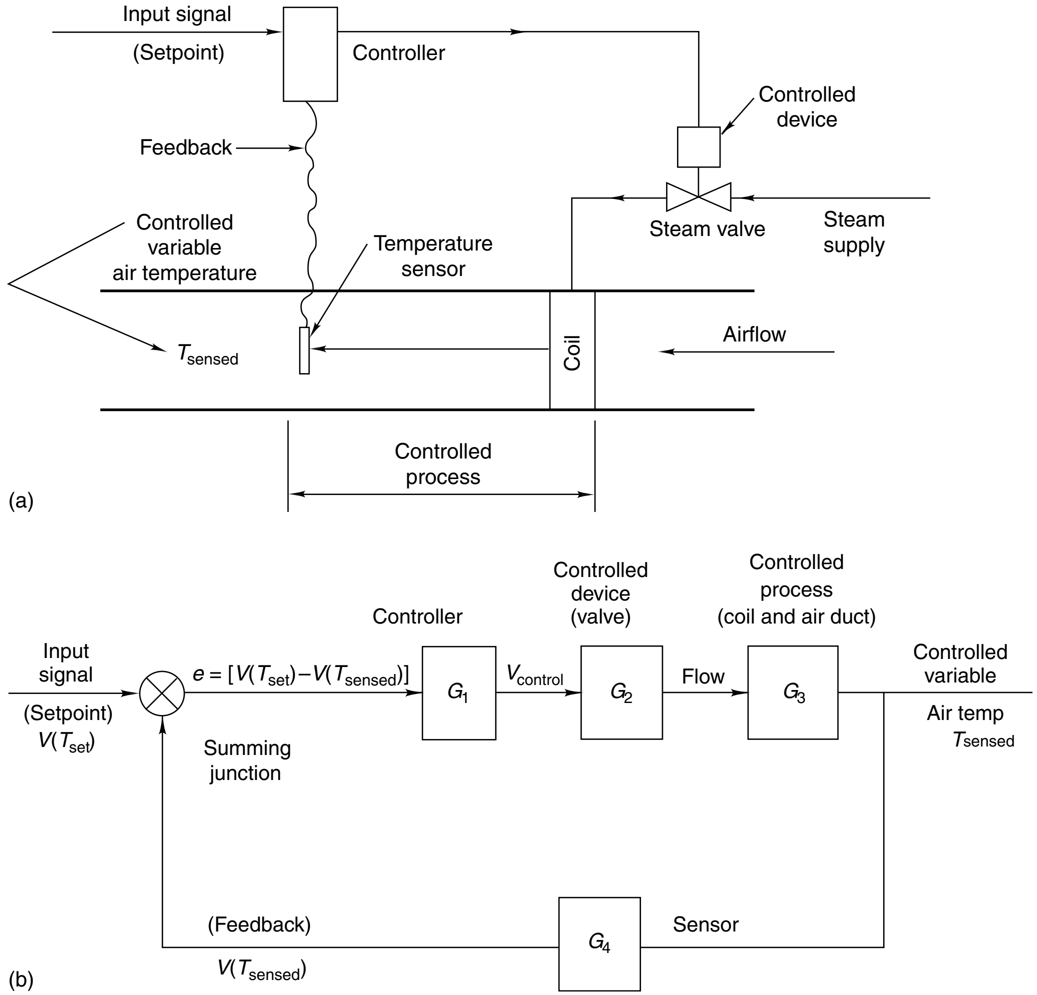

FIGURE 6.2 (a) Simple heating coil control system showing the process (coil and short duct length), controller, controlled device (valve and its actuator) and sensor. The setpoint entered externally is the desired coil outlet temperature. (b) Equivalent control diagram for heating coil. The G's represent functions relating the input to the output of each module. Voltages, V, represent both temperatures (setpoint and coil outlet) and the controller output to the valve in electronic control systems.

As coil air-outlet temperature drops farther below the set temperature, error increases, leading to increased control action—an increased steam flow rate. Note that the temperatures in Equation 6.1 and Equation 6.2 are often replaced by voltages or other variables, particularly in electronic controllers.

The throttling range (ΔT_{max}) is the total change in the controlled variable that is required to cause the actuator or controlled device to move between its limits. For example, if the nominal temperature of a zone is 72°F and the heating controller throttling range is 6°F, then the heating control undergoes its full travel between a zone temperature of 69°F and 75°F. This control, whose characteristic is shown in Figure 6.4, is reverse acting; i.e., as temperature (controlled variable) increases, the heating valve position decreases.

The throttling range is inversely proportional to the gain as shown in Figure 6.4. Beyond the throttling range, the system is out of control. In actual hardware, one can set the setpoint and either the gain or the

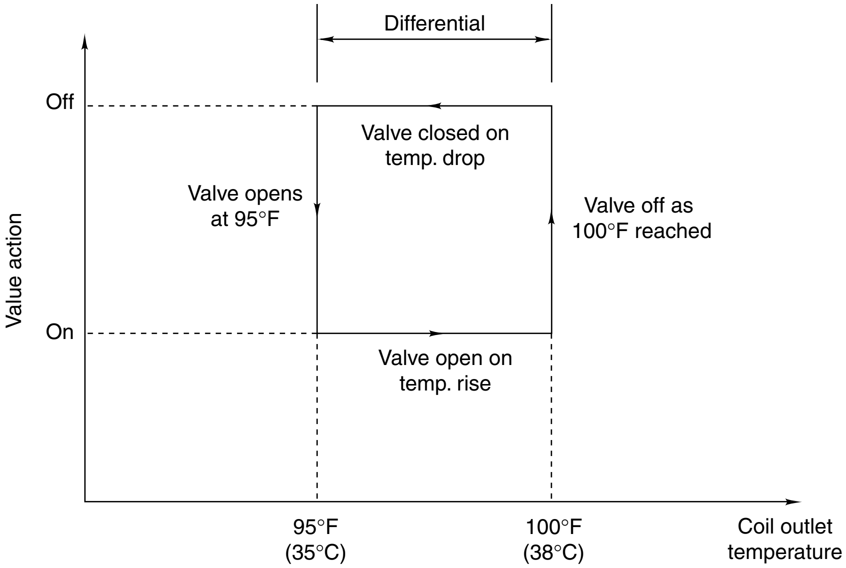

FIGURE 6.3 Two position (on-off) control characteristic.

throttling range (most common), but not both of the latter. Proportional control by itself is not capable of reducing the error to zero because an error is needed to produce the capacity required for meeting a load, as will be discussed in the following example. This unavoidable value of the error in proportional systems is called the *offset*. It is easy to see from Figure 6.4 that the offset is larger for systems with smaller gains. There is a limit to which one can increase the gain to reduce offset, because high gains can produce control instability.

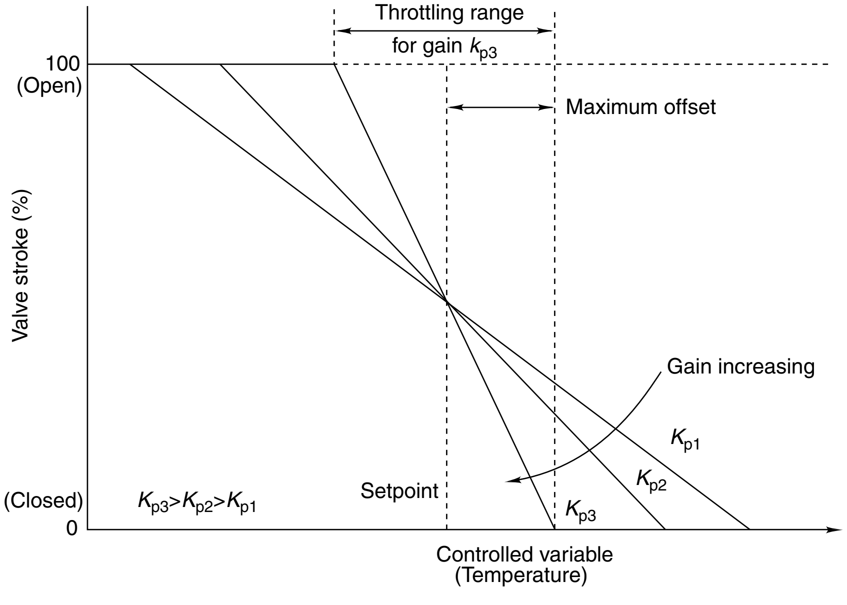

FIGURE 6.4 Proportional control characteristic showing various throttling ranges and the corresponding proportional gains, K_p. This characteristic is typical of a heating coil temperature controller.

Example 6.1 Proportional Gain Calculation

Problem: If the steam heating coil in Figure 6.2a has a heat output that varies from 0 to 20 kW as the outlet air temperature varies from 35 to 45°C in an industrial process, what is the coil gain and what is the throttling range? Find an equation relating the heat rate at any sensed air temperature to the maximum rate in terms of the gain and setpoint.

Solution: Given that $\dot{Q}_{\max} = 20\text{ kW}$, $\dot{Q}_{\min} = 0\text{ kW}$, $T_{\max} = 45°\text{C}$, and $T_{\min} = 35°\text{C}$ for the system in Figure 6.2a, and assuming steady-state operation, the problem is to determine K_p and $\Delta T_{\max}$.

The throttling range is the range of the controlled variable (air temperature) over which the controlled system (heating coil) exhibits its full capacity range. The temperature varies from 35 to 45°C; therefore the throttling range is

$$\Delta T_{\max} = 45°\text{C} - 35°\text{C} = 10°\text{C} \tag{6.3}$$

The proportional gain is the ratio of the controlled system (coil) output to the throttling range. For this example, the controller output is $\dot{Q}$ and the gain is

$$K_p = \frac{\dot{Q}_{\max} - \dot{Q}_{\min}}{\Delta T_{\max}} = \frac{(20-0)\text{ kW}}{10\text{ K}} = 2.0(\text{kW/K}). \tag{6.4}$$

The controller characteristic can be found by inspecting Figure 6.4. It is assumed that the average air temperature (40°C) occurs at the average heat rate (10 kW). The equation of the straight line shown is

$$\dot{Q} = K_p(T_{\text{set}} - T_{\text{sensed}}) + \frac{\dot{Q}_{\max}}{2} = K_p e + \frac{\dot{Q}_{\max}}{2}. \tag{6.5}$$

Note that the quantity ($T_{\text{set}} - T_{\text{sensed}}$) is the error, e, and a nonzero value indicates that the set temperature is not met. However, the proportional control system used here requires presence of an error signal to fully open or fully close the valve.

Inserting the numerical values:

$$\dot{Q} = 2.0\frac{\text{kW}}{\text{K}}(40 - T_{\text{sensed}}) + 10\text{ kW}. \tag{6.6}$$

Comments: In an actual steam-coil control system, it is the steam valve that is controlled directly to indirectly control the heat rate of the coil. This is typical of many HVAC system controls, in that the desired control action is achieved indirectly by controlling another variable that in turn accomplishes the desired result. This is why the controller and controlled device are often shown separately as in Figure 6.2b.

This example illustrates with a simple system how proportional control uses an error signal to generate an offset, and how that offset controls an output quantity. Using a bias value, the error can be set to be zero at one value in the control range. Proportional control requires a nonzero error over the remainder of the control range.

Real systems also have a time response called a *loop time constant*. This limits proportional control applications to slow response systems, where the throttling range can be set so that the system achieves stability. Typically, slow-responding mechanical systems include pneumatic thermostats for zone control and air handler unit damper control. Fast-acting systems like duct pressure control must be artificially slowed down to be appropriate for proportional control.

Integral control is often added to proportional control to eliminate the offset inherent in proportional-only control. The result—proportional plus integral control—is identified by the acronym PI. Initially, the corrective action produced by a PI controller is the same as for a proportional-only controller. After the initial period, a further adjustment due to the integral term reduces the offset to zero. The rate at which this occurs depends on the time scale of the integration. In equation form, the PI controller is modeled by

$$V = V_0 + K_p e + K_i \int e\,\mathrm{d}t, \tag{6.7}$$

in which K_i is the integral gain constant. It has units of reciprocal time and is the number of times that the integral term is calculated per unit time. This is also known as the *reset rate; reset control* is an older term used by some to identify integral control.

Today, most PI control implementations use electronic sensors, analog-to-digital converters (A/Ds), and digital logic to implement the PI control. Integral windup must be taken into account when using PI control. Integral windup occurs when the control first starts or comes out of a reset condition. The integral term increases by integrating the error signal, and can have a full output. When the control becomes enabled, a large offset error can occur, driving the output variable to an undesired state. Various methods exist to minimize or eliminate the windup problem.

The integral term in Equation 6.7 has the effect of adding a correction to the output signal V for as long as the error term exists. The continuous offset produced by the proportional-only controller can thereby be reduced to zero because of the integral term. For HVAC systems, the time scale (K_P/K_i) of the integral term is often in the range of 10+ s to 10+ min. PI control is used for fast-acting systems for which accurate control is needed. Examples include mixed air controls, duct static pressure controls, and coil controls. Because the offset is eventually eliminated with PI control, the throttling range can be set rather wide to insure stability under a wider range of conditions than good control would permit with proportional-only control. Therefore, PI control is also used on almost all electronic thermostats.

Derivative control is used to speed up the action of PI control. When derivative control is added to PI control, the result is called *PID control*. The derivative term added to Equation 6.7 generates a correction signal proportional to the time rate of change of error. This term has little effect on a steady proportional system with uniform offset (time derivative is zero) but initially, after a system disturbance, produces a larger correction more rapidly. Equation 6.8 includes the derivative term in the mathematical model of the PID controller

$$V = V_0 + K_p e + K_i \int e\,\mathrm{d}t + K_d \frac{\mathrm{d}e}{\mathrm{d}t}, \tag{6.8}$$

in which K_d is the derivative gain constant. The time scale (K_d/K_p) of the derivative term is typically in the range of 0.2–15 minutes. Because HVAC systems do not often require rapid control response, the use of PID control is less common than use of PI control. Because a derivative is involved, any noise in the error (i.e., sensor) signal must be avoided to maintain stable control. One effective application of PID control in buildings is in duct static pressure control, a fast-acting subsystem that otherwise has a tendency to be unstable.

Derivative control has limited application in HVAC systems because the PID control loops can easily become unstable. PID loops require correct tuning for each of the three gain constants (Ks) over the performance range that the control loop will need to operate. Another serious limitation centers on the fact that most facility operators lack training and skills in tuning PID control loops.

Figure 6.5 illustrates the loop response for three correctly configured systems when a step function change, or disturbance, occurs. Note that the PI loop achieves the same final control as the PID, only the PI error signal is larger. An improperly configured PID loop can oscillate from the high value to the low value continuously.

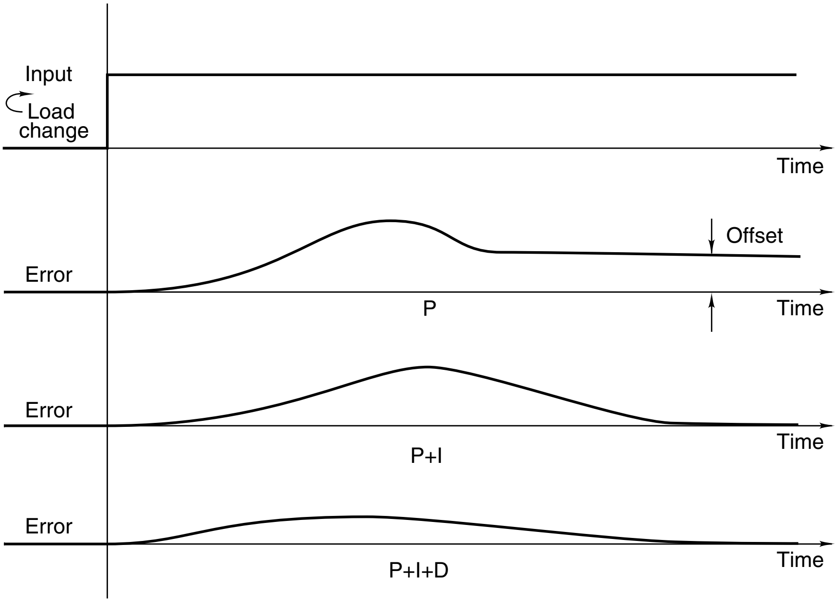

FIGURE 6.5 Performance comparison of P, PI, and PID controllers when subjected to a uniform, input step change.

6.3 Basic Control Hardware

In this section, the various physical components needed to perform the actions required by the control strategies of the previous section are described. Because there are two fundamentally different control approaches—pneumatic and electronic—the following material is so divided. Sensors, controllers, and actuators for principal HVAC applications are described.

6.3.1 Pneumatic Systems

The first widely adopted automatic control systems used compressed air as the signaling transmission medium. Compressed air had the advantages that it could be "metered" through various sensors, and it could power large actuators. The fact that the response of a normal pneumatic loop could take several minutes often worked as an advantage, as well. Pneumatic controls use compressed air (approximately 20 psig in the US) for operation of sensors and actuators. Though most new buildings use electronic controls, many existing buildings use pneumatic controls. This section provides an overview of how these devices operate.

Temperature control and damper control comprise the bulk of pneumatic loop controls. Figure 6.6 shows a method of sensing temperature and producing a control signal. Main supply air, supplied by a compressor, enters a branch line through a restriction. The zone thermostat bleeds out a variable amount of air, depending on the position of the flapper, controlled by the temperature sensor bellows. As more air bleeds out, the branch line pressure (control pressure) drops. This reduction in the total pressure to the control element changes the output of the control element. This control can be forward-acting or reverse-acting. The restrictions typically have hole diameters on the order of a few thousandths of an inch, and consume very little air. Typical pressures in the branch lines range between 3 and 13 psig (20–90 kPa). In simple systems this pressure from a thermostat could operate an actuator such as a control valve for a room heating unit. In this case, the thermostat is both the sensor and the controller—a rather common configuration.

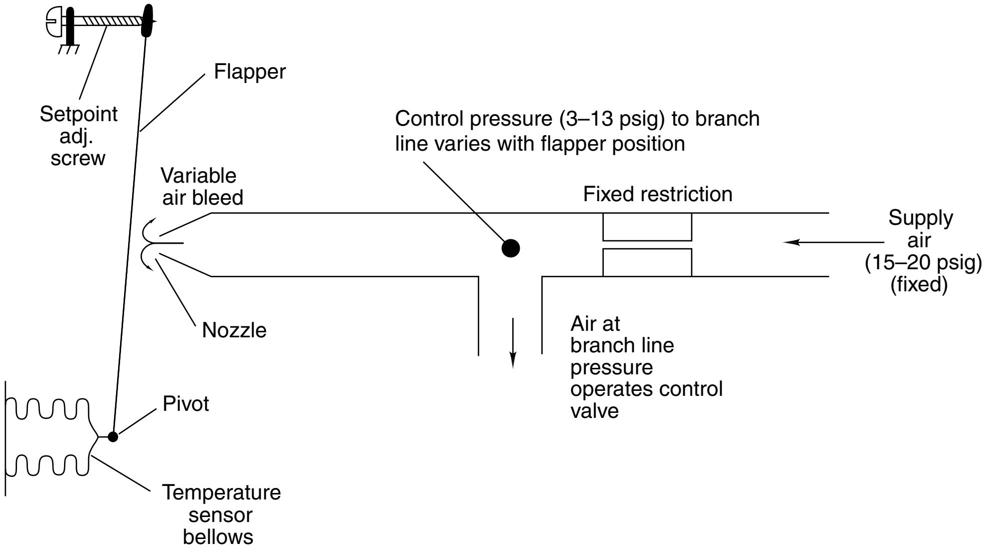

FIGURE 6.6 Drawing of pneumatic thermostat showing adjustment screw used to change temperature setting.

Many other temperature sensor approaches can be used. For example, the bellows shown in Figure 6.6 can be eliminated, and the flapper can be made of a bimetallic strip. As temperature changes, the bimetallic strip changes curvature, opening or closing the flapper/nozzle gap. Another approach uses a remote bulb filled with either liquid or vapor that pushes a rod (or a bellows) against the flapper to control the pressure signal. This device is useful if the sensing element must be located where direct measurement of temperature by a metal strip or bellows is not possible, such as in a water stream or high-velocity ductwork. The bulb and connecting capillary size may vary considerably by application.

Pressure sensors may use either bellows or diaphragms to control branch line pressure. For example, the motion of a diaphragm may replace that of the flapper in Figure 6.6 to control the bleed rate. A bellows similar to that shown in the same figure may be internally pressurized to produce a displacement that can control air bleed rate. A bellows produces significantly greater displacements than a single diaphragm.

Humidity sensors in pneumatic systems are made from materials that change size with moisture content. Nylon or other synthetic hygroscopic fibers that change size significantly (i.e., 1%–2%) with humidity are commonly used. Because the dimensional change is relatively small on an absolute basis, mechanical amplification of the displacement is used. The materials that exhibit the desired property include nylon, hair, and cotton fibers. Human hair exhibits a much more linear response with humidity than nylon; however, because the properties of hair vary with age, nylon has much wider use (Letherman 1981). Humidity sensors for electronic systems are quite different and are discussed in the next section.

An actuator converts pneumatic energy to motion—either linear or rotary. It creates a change in the controlled variable by operating control devices such as dampers or valves. Figure 6.7 shows a pneumatically operated control valve. The valve opening is controlled by the pressure in the diaphragm acting against the spring. The spring is essentially a linear device. Therefore, the motion of the valve stem is essentially linear with air pressure. However, this does not necessarily produce a linear effect on flow, as discussed later. Figure 6.8 shows a pneumatic damper actuator. Linear actuator motion is converted into rotary damper motion by the simple mechanism shown.

Pneumatic controllers produce a branch line (see Figure 6.6) pressure that is appropriate to produce the needed control action for reaching the setpoint. Such controls are manufactured by a number of control firms for specific purposes. Classifications of controllers include the sign of the output (direct- or reverse-acting) produced by an error, by the control action (proportional, PI, or two-position), or by number of inputs or outputs. Figure 6.9 shows the essential elements of a dual-input, single-output

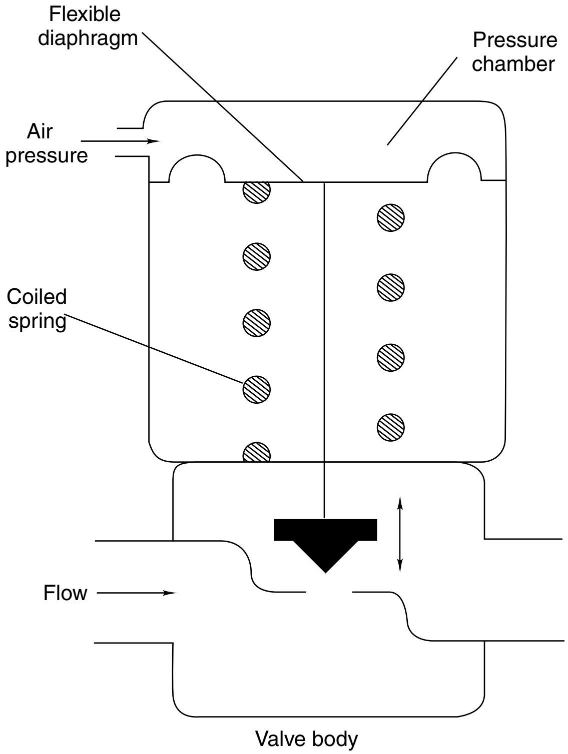

FIGURE 6.7 Pneumatic control valve showing counterforce spring and valve body. Increasing pressure closes the valve.

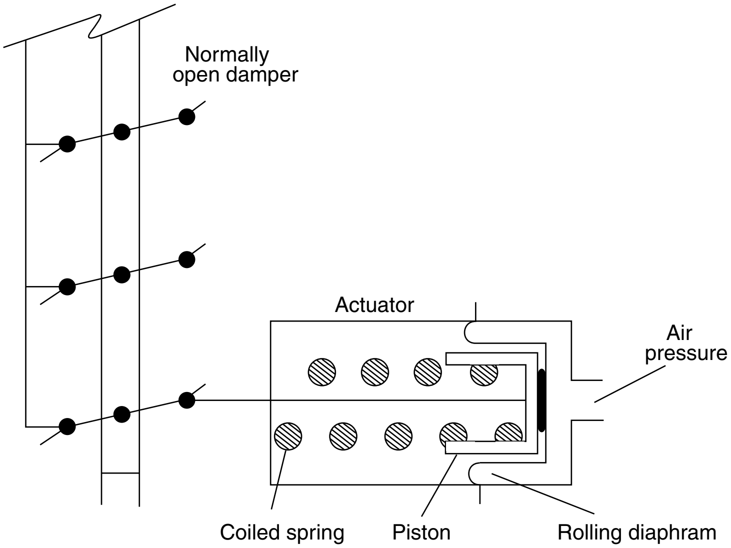

FIGURE 6.8 Pneumatic damper actuator. Increasing pressure closes the parallel blade damper.

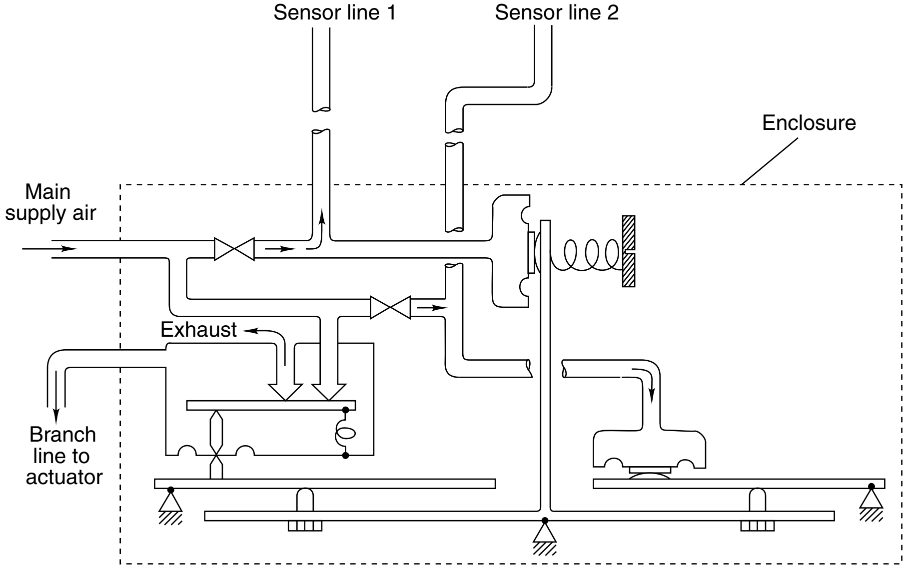

FIGURE 6.9 Example pneumatic controller with two inputs and one control signal output.

controller. The two inputs could be heating system supply temperature and outdoor temperature sensors, used to control the output water temperature setting of a boiler in a building heating system. This is essentially a boiler temperature reset system that reduces heating water temperature with increasing ambient temperature for better system control and reduced energy use.

The air supply for pneumatic systems must produce very clean, oil-free, dry air. A compressor producing 80–100 psig is typical. Compressed air is stored in a tank for use as needed, avoiding continuous operation of the compressor. The air system should be oversized by 50%–100% of estimated nominal consumption. The air is then dried to prevent moisture freezing in cold control lines in air handling units and elsewhere. Dried air should have a dew point of −30°F or less in severe heating climates. In deep cooling climates, the lowest temperature to which the compressed air lines are exposed may be the building cold air supply. Next, the air is filtered to remove water droplets, oil (from the compressor), and any dirt. Finally, the air pressure is reduced in a pressure regulator to the control system operating pressure of approximately 20 psig. Control air piping uses either copper or, in accessible locations, nylon.

6.3.2 Electronic Control Systems

Electronic controls comprise the bulk of the controllers for HVAC systems. Direct digital control systems (DDCs) began to make inroads in the early 1990s and now make up over 80% of all controller sales. Low-end microprocessors now cost under $0.50 each and are thus very economical to apply. Along with the decreased cost, increased functionality can be obtained with DDC controls. BACnet has emerged as the standard communication protocol (ASHRAE 2001), and most control vendors offer a version of the BACnet protocol. In this section, the sensors, actuators and controllers used in modern electronic control systems for buildings are surveyed.

Direct digital control (DDC) enhances the previous analog-only electronic system with digital features. Modern DDC systems use analog sensors (converted to digital signals within a computer) along with digital computer programs to control HVAC systems. The output of this microprocessor-based system can be used to control electronic, electrical, or pneumatic actuators or a combination. DDC systems have the advantage of reliability and flexibility that others do not. For example, it is easier to accurately set control constants in computer Software than by making adjustments at a control panel with a

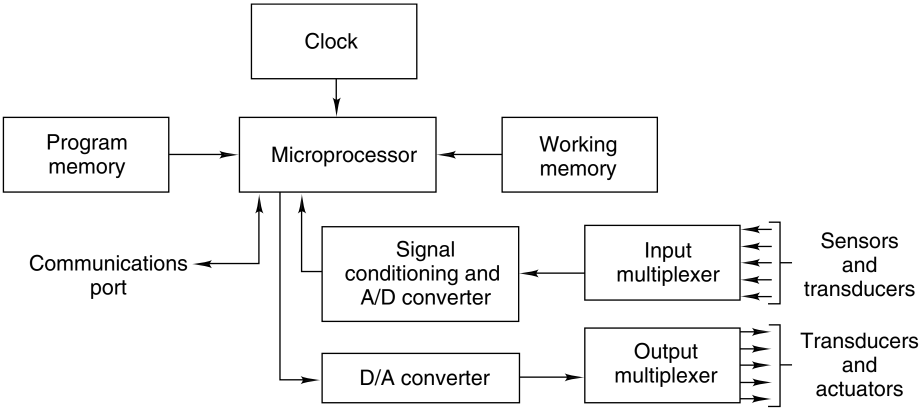

FIGURE 6.10 Block diagram of DDC controller.

screwdriver. DDC systems offer the option of operating energy management systems (EMS) and HVAC diagnostic, knowledge-based systems because the sensor data used for control is very similar to that used in EMSs. Pneumatic systems do not offer this ability. Figure 6.10 shows a schematic diagram of a DDC controller. The entire control system must include sensors and actuators not shown in this controller-only drawing.

Temperature measurements for DDC applications are made by three principal methods:

- Thermocouples
- Resistance temperature detectors (RTDs)
- Thermistors

Each has its advantages for particular applications. Thermocouples consist of two dissimilar metals chosen to produce a measurable voltage at the temperature of interest. The voltage output is low (in the millivolt range) but a well-established function of the junction temperature. Except for flame temperature measurements, thermocouples produce voltages too small to be useful in most HVAC applications (for example, a type-J thermocouple produces only 5.3 mV at 100°C).

RTDs use small, responsive sensing sections constructed from metals whose resistance-temperature characteristic is well established and reproducible. To first order,

$$R = R_0(1 + kT), \tag{6.9}$$

where R is the resistance (Ω), R_0 is the resistance at the reference temperature of 0°C (Ω), k is the temperature coefficient of resistance ($°C^{-1}$), and T is the RTD temperature (°C). This equation is easy to invert to find the temperature as a function of resistance. Although complex higher-order expressions exist, their use is not needed for HVAC applications.

Two common materials for RTDs are platinum and Balco (a 40%-nickel, 60%-iron alloy). The nominal values of k, respectively, are 3.85×10^{-3} and $4.1\times10^{-3}\ °C^{-1}$.

Modern electronics measure current and voltage and then determine the resistance using Ohm's law. The measurement causes power dissipation in the RTD element, raising the temperature and creating an error in the measurement. This Joule self-heating can be minimized by reducing the power dissipated in the RTD. Raising the resistance of the RTD helps reduce self-heating, but the most effective approach requires pulsing the current and making the measurement in a few milliseconds. Because one measurement per second will generally satisfy the most demanding HVAC control loop, the power dissipation can be reduced by a factor of 100 or more. Modern digital controls can easily handle the calculations necessary to implement piecewise linearization and other curve-fitting methods to improve the accuracy of the RTD measurements. In addition, lead wire resistance can cause lack of accuracy for the class of platinum RTDs whose nominal resistance is only 100 Ω, because the lead resistance of 1–2 Ω is not negligible by comparison to that of the sensor itself.

Thermistors are semiconductors that exhibit a standard exponential dependence for resistance versus temperature given by

$$R = Ae^{(B/T)}. \tag{6.10}$$

A is related to the nominal value of resistance at the reference temperature (77°F) and is on the order of several thousands of ohms. The exponential coefficient B (a weak function of temperature) is on the order of 5400–7200 R (3000–4000 K). The nonlinearity inherent in a thermistor can be reduced by connecting a properly selected fixed resistor in parallel with it. The resulting linearity is desirable from a control system design viewpoint. Thermistors can have a problem with long-term drift and aging; the designer and control manufacturer should consult on the most stable thermistor design for HVAC applications. Some manufacturers provide linearized thermistors that combine both positive and negative resistive dependence on temperature to yield a more linear response function.

Humidity measurements are needed for control of enthalpy economizers, or may also be needed to control special environments as such as clean rooms, hospitals and areas housing computers. Relative humidity, dew point, and humidity ratio are all indicators of the moisture content of air. An electrical, capacitance-based approach using a polymer with interdigitated electrodes has become the most common sensor type. The polymer material absorbs moisture and changes the dielectric constant of the material, changing the capacitance of the sensor. The capacitance of the sensor forms part of a resonant circuit so that when the capacitance changes, the resonant frequency changes. This frequency can then be correlated to the relative humidity and provide reproducible readings, if not saturated by excessive exposure to high humidity levels (Huang 1991). The response times of tens of seconds easily satisfy most HVAC application requirements. These humidity sensors need frequent calibration, generally yearly. If a sensor becomes saturated or has condensation on the surface, it becomes uncalibrated and exhibits an offset from its calibration curve. Older technologies used ionic salts on gold grids. These expensive sensors failed frequently.

Pressure measurements are made by electronic devices that depend on a change of resistance or capacitance with imposed pressure. Figure 6.11 shows a cross-sectional drawing of each. In the resistance type, stretching of the membrane lengthens the resistive element, thereby increasing resistance. This resistor is an element in a Wheatstone bridge; the resulting bridge voltage imbalance is linearly related to the imposed pressure. The capacitative-type unit has a capacitance between a fixed and a flexible metal that decreases with pressure. The capacitance change is amplified by a local amplifier that produces an output signal proportional to pressure. Pressure sensors can burst from overpressure or a water-hammer effect. Installation must carefully follow the manufacturer's requirements.

DDC systems require flow measurements to determine the energy flow for air and water delivery systems. Pitot tubes (or arrays of tubes) and other flow measurement devices can be used to measure either air or liquid flow in HVAC systems. Air flow measurements allow for proper flow in variable air volume (VAV) system control, building pressurization control and outside air control. Water flow measurements enable chiller and boiler control, and monitoring of various water loops used in the HVAC system. Some controls require only the knowledge of flow being present. Open–closed sensors fill this need and typically have a paddle that makes a switch connection in the presence of flow. These types of switches can also be used to detect "end of range," i.e., fully open or closed for dampers and other mechanical control elements.

Temperature, humidity and pressure transmitters are often used in HVAC systems. They amplify signals produced by the basic devices described in the preceding paragraphs and produce an electrical signal over a standard range, thereby permitting standardization of this aspect of DDC systems. The standard ranges are

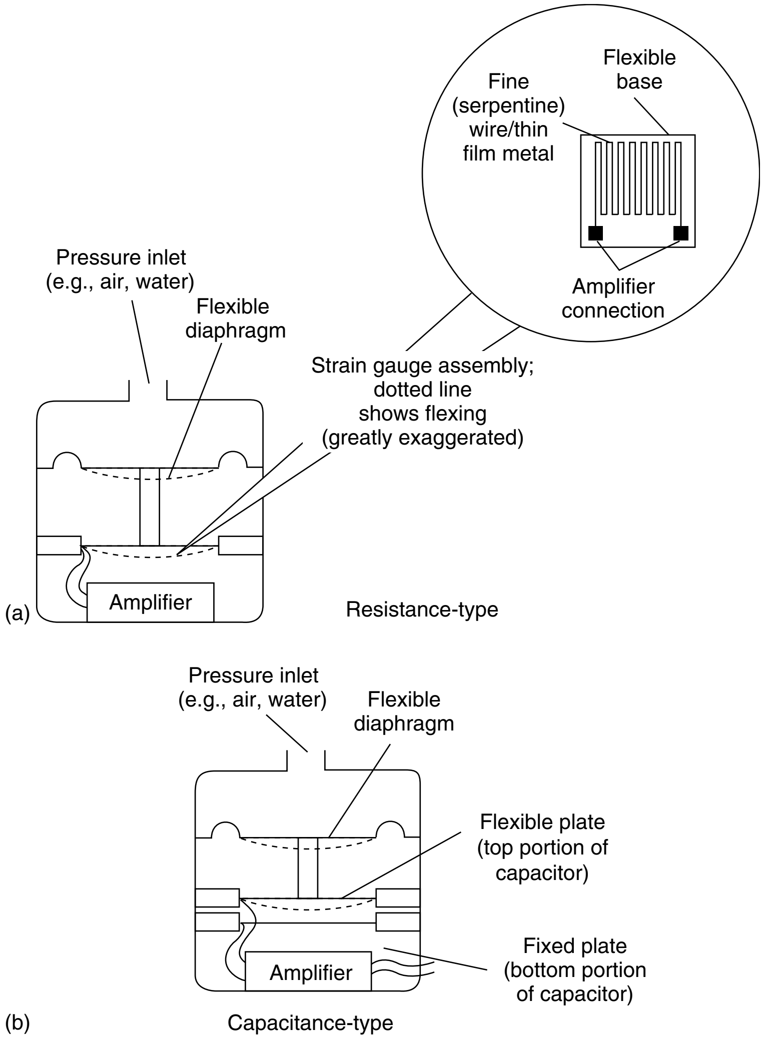

FIGURE 6.11 Resistance and capacitance type pressure sensors.

Current: 4–20 ma (DC)
Voltage: 0–10 volts (DC)

Although the majority of transmitters produce such signals, the noted values are not universally used.

Figure 6.10 shows the elements of a DDC controller. The heart of the controller is a microprocessor that can be programmed in either a standard or system-specific language. Control algorithms (linear or not), sensor calibrations, output signal shaping, and historical data archiving can be programmed as the user requires. A number of firms have constructed controllers on standard personal computer platforms. It is beyond the scope of this chapter to describe the details of programming HVAC controllers because each manufacturer uses a different approach. The essence of any DDC system, however, is the same as shown in the figure. Honeywell (1988) discusses DDC systems and their programming in more detail. Actuators for electronic control systems include

- Motors—operate valves, dampers
- Variable speed controls—pump, fan, chiller drives

- Relays and motor starters—operate other mechanical or electrical equipment (pumps, fans, chillers, compressors), electrical heating equipment
- Transducers—for example, convert electrical signal to pneumatic (EP transducer)
- Visual displays—not actuators in the usual sense, but used to inform system operator of control and HVAC system function

Pneumatic and DDC systems have their own advantages and disadvantages. Pneumatic systems possess increasing disadvantages of cost, hard to find replacements, requiring an air compressor with clean oil-free air, sensor drift, and imprecise control. The retained advantages include explosion-proof operation and a fail-soft degradation of performance. DDC systems have emerged and have taken the lead over pneumatic controls for HVAC systems because of the ability to integrate the control system into a large energy management and control system (EMCS), the accuracy of the control, and the ability to diagnose problems remotely. Systems based on either technology require maintenance and skilled operators.

6.4 Basic Control System Design Considerations

This section discusses selected topics in control system design, including control system zoning, valve and damper selection, and control logic diagrams. The following section shows several HVAC system control design concepts. Bauman (1998) may be consulted for additional information.

The ultimate purpose of an HVAC control system is to control zone temperature (and secondarily air motion and humidity) to conditions that assure maximum comfort and productivity of the occupants. From a controls viewpoint, the HVAC system is assumed to be able to provide comfort conditions if controlled properly. A zone is any portion of a building having loads that differ in magnitude and timing sufficiently from those of other areas, such that separate portions of the secondary HVAC system and control system are needed to maintain comfort.

Having specified the zones, the designer must select the location for the thermostat (and other sensors, if used). Thermostat signals are either passed to the central controller or used locally to control the amount and temperature of conditioned air or coil water introduced into a zone. The air is conditioned either locally (e.g., by a unit ventilator or baseboard heater) or centrally (e.g., by the heating and cooling coils in the central air handler). In either case, a flow control actuator is controlled by the thermostat signal. In addition, airflow itself may be controlled in response to zone information in VAV systems. Except for variable speed drives used in variable volume air or liquid systems, flow is controlled by valves or dampers. The design selection of valves and dampers is discussed next.

6.4.1 Steam and Liquid Flow Control

The flow through valves such as that shown in Figure 6.7 is controlled by valve stem position, which determines the flow area. The variable flow resistance offered by valves depends on their design. The flow characteristic may or may not be linear with position. Figure 6.12 shows flow characteristics of the three most common valve types. Note that the plotted characteristics apply only for constant valve pressure drop. The characteristics shown are idealizations of actual valves. Commercially available valves will resemble, but not necessarily exactly match, the curves shown.

The linear valve has a proportional relation between volumetric flow, $\dot{V}$, and valve stem position, z.

$$\dot{V} = kz. \tag{6.11}$$

The flow in equal percentage valves increases by the same fractional amount for each increment of opening. In other words, if the valve is opened from 20 to 30% of full travel, the flow will increase by the same percentage as if the travel had increased from 80 to 90% of its full travel. However, the absolute volumetric flow increase for the latter case is much greater than for the former. The equal percentage

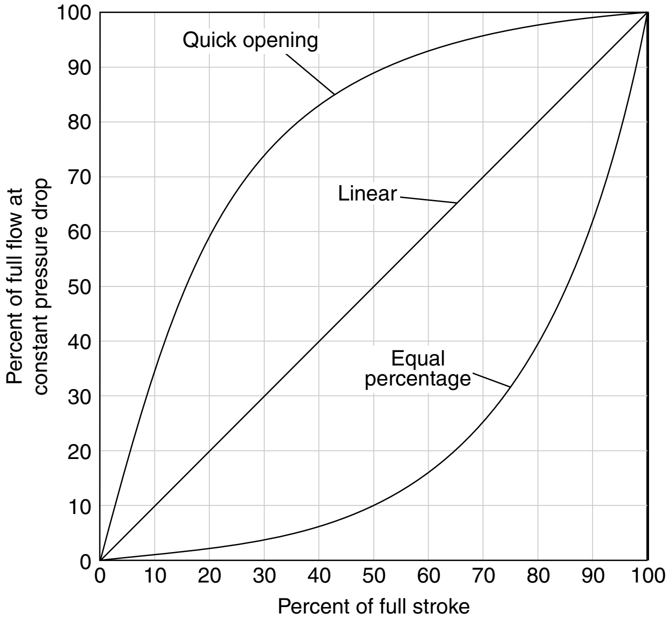

FIGURE 6.12 Quick opening, linear and equal percentage valve characteristics.

valve flow characteristic is given by

$$\dot{V} = K\mathrm{e}^{(kz)}, \tag{6.12}$$

in which k and K are proportionality constants for a specific valve. Quick-opening valves do not provide good flow control, but are used when rapid action is required with little stem movement for on/off control.

Example 6.2 Equal Percentage Valve

Problem: A valve at 30% of travel has a flow of 4 gal/min. If the valve opens another 10% and the flow increases by 50% to 6 gal/min, what are the constants in Equation 6.12? What will be the flow at 50% of full travel? (See Figure 6.12.)

Assumptions: Pressure drop across the valve remains constant.

Solution: The problem is to determine k, K, $\dot{V}_{50}$. Equation 6.12 can be evaluated at the two flow conditions. If the results are divided by each other, then

$$\frac{\dot{V}_2}{\dot{V}_1} = \frac{6}{4} = \mathrm{e}^{k(z_2-z_1)} = \mathrm{e}^{k(0.4-0.3)}. \tag{6.13}$$

In this expression, the travel, z, is expressed as a fraction of the total travel and is dimensionless. Solving this equation for k gives the result

$$k = 4.05 \text{ (no units)}$$

From the known flow at 30% travel, the second constant, K, can be determined:

$$K = \frac{4 \text{ gal/min}}{\mathrm{e}^{4.05\times 0.3}} = 1.19 \text{ gal/min}. \tag{6.14}$$

Finally, the flow is given by

$$\dot{V} = 1.19\mathrm{e}^{4.05z}. \tag{6.15}$$

At 50% travel, the flow can be found from

$$\dot{V}_{50} = 1.19\mathrm{e}^{4.05\times 0.5} = 9.0\ \text{gal/min}. \tag{6.16}$$

Comments: This result can be checked because the valve is an equal percentage valve. At 50% travel, the valve has moved 10% beyond its 40% setting, at which the flow was 6 gal/min. Another 10% stem movement will result in another 50% flow increase from 6 gal/min to 9 gal/min, confirming the solution.

The plotted characteristics of all three valve types assume constant pressure drop across the valve. In an actual system, the pressure drop across a valve will not remain constant, but if the valve is to maintain its control characteristics, the pressure drop across it must be the majority of the entire loop pressure drop. If the valve is designed to have a full open-pressure drop equal to that of the balance of the loop, good flow control will exist. This introduces the concept of valve authority, defined as valve pressure drop as a fraction of total system pressure drop:

$$A \equiv \frac{\Delta p_{\mathrm{v,open}}}{(\Delta p_{\mathrm{v,open}} + \Delta p_{\mathrm{system}})}. \tag{6.17}$$

For proper control, the full-open valve authority should be at least 0.5. If the authority is 0.5 or more, control valves will have installed characteristics not much different from those shown in Figure 6.12. If not, the valve characteristic will be distorted upward because the majority of the system pressure drop will be dissipated across the valve.

Valves are further classified by the number of connections or ports. Figure 6.13 shows sections of typical two-way and three-way valves. Two-port valves control flow through coils or other HVAC equipment by varying valve flow resistance as a result of flow area changes. As shown, the flow must oppose the closing of the valve. If not, near closure the valve would slam shut or oscillate, both of which cause excessive wear and noise. The three-way valve shown in the figure is configured in the diverting mode. That is, one stream is split into two, depending on the valve opening. The three-way valve shown is double seated (single-seated three-way valves are also available); it is therefore easier to close than a single-seated valve, but tight shutoff is not possible.

Three-way valves can also be used as mixing valves. In this application two streams enter the valve, and one leaves. Because their internal design is different, mixing and diverting valves cannot be used interchangeably, to ensure that they can each seat properly. Particular attention is needed by the installer to be sure that connections are made properly; arrows cast in the valve body show the proper flow direction. Figure 6.14 shows an example of three-way valves for both mixing and diverting applications.

Valve flow capacity is denoted in the industry by the dimensional flow coefficient, C_v, defined by

$$\dot{V}(\text{gal/min}) = C_v[\Delta p(\text{psi})]^{0.5}. \tag{6.18}$$

Δp is the pressure drop across the fully open valve, so C_v is specified as the flow rate of 60°F water that will pass through the fully open valve if a pressure difference of 1.0 psi is imposed across the valve. If SI units (m^3/s and Pa) are used, the numerical value of C_v is 17% larger than in USCS units. After the designer has determined a value of C_v, manufacturer's tables can be consulted to select a valve for the known pipe size. If a fluid other than water is to be controlled, the C_v found from Equation 6.18 should be multiplied by the square root of the fluid's specific gravity.

Steam valves are sized using a similar dimensional expression

$$\dot{m}(\text{lb/h}) = 63.5C_v[\Delta p(\text{psi})/v(\text{ft.}^3/\text{lb})]^{0.5}, \tag{6.19}$$

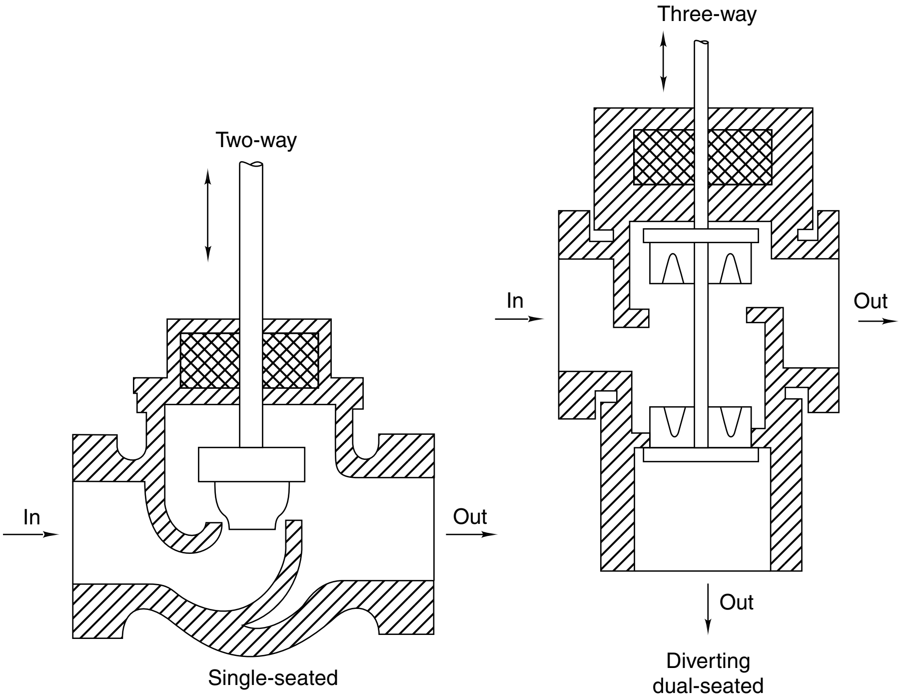

FIGURE 6.13 Cross-sectional drawings of direct-acting, single-seated, two-way valve and dual-seated, three-way, diverting valve.

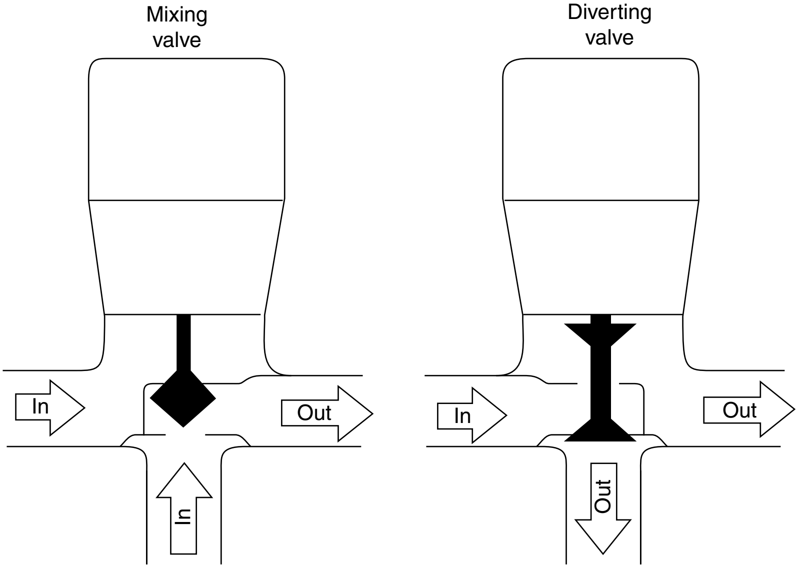

FIGURE 6.14 Three-way mixing and diverting valves. Note the significant difference in internal construction. Mixing valves are more commonly used.

in which v is the steam specific volume. If the steam is highly superheated, multiply C_v found from Equation 6.19 by 1.07 for every 100°F of superheat. For wet steam, multiply C_v by the square root of the steam quality. Honeywell (1988) recommends that the pressure drop across the valve to be used in the equation be 80% of the difference between steam supply and return pressures (subject to the sonic flow limitation discussed below). Table 6.1 can be used for preliminary selection of control valves for either steam or water.

The type of valve (linear or not) for a specific application must be selected so that the controlled system is as nearly linear as possible. Control valves are very commonly used to control the heat transfer rate in coils. For a linear system, the combined characteristic of the actuator, valve, and coil should be linear. This will require quite different valves for hot water and steam control, for example.

Figure 6.15 shows the part load performance of a hot water coil used for air heating; at 10% of full flow the heat rate is 50% of its peak value. The heat rate in a cross-flow heat exchanger increases roughly in exponential fashion with flow rate—a highly nonlinear characteristic. This heating coil nonlinearity follows from the longer water residence time in a coil at reduced flow, and the relatively large temperature difference between air being heated and the water heating it.

However, if one were to control the flow through this heating coil by an equal percentage valve (positive exponential increase of flow with valve position), the combined valve plus coil characteristic would be roughly linear. Referring to Figure 6.15, 50% of stem travel corresponds to 10% flow. The third graph in the figure is the combined characteristic. This near-linear subsystem is much easier to control than if a linear valve were used with the highly nonlinear coil. Hence the rule: use equal percentage valves for heating coil control.

Linear, two-port valves are to be used for steam flow control to coils because the transfer of heat by steam condensation is a linear, constant temperature process—the more steam supplied, the greater the heat rate, in exact proportion. Note that this is a completely different coil flow characteristic than for hot-water coils. However, steam is a compressible fluid and the sonic velocity sets the flow limit for a given valve opening when the pressure drop across the valve is more than 60% of the steam supply line absolute pressure. As a result, the pressure drop to be used in Equation 6.19 is the *smaller* of (1) 50% of the absolute stream pressure upstream of the valve or (2) 80% of the difference between the steam supply and return line pressures. The 80% rule gives good valve modulation in the subsonic flow regime (Honeywell 1988).

Chilled water control valves should also be linear because the performance of chilled water coils (smaller air–water temperature difference than in hot-water coils) is more similar to steam coils than to hot-water coils.

Either two- or three-way valves can be used to control flow at part load through heating and cooling coils as shown in Figure 6.16. The control valve can be controlled from either coil outlet water or air temperature. Two- or three-way valves achieve the same local result at the coil when used for part load control. However, the designer must consider effects on the balance of the secondary system when selecting the valve type.

In essence, the two-way valve flow control method results in variable flow (tracking variable loads) with constant coil water temperature change, whereas the three-way valve approach results in roughly constant secondary loop flow rate, but smaller coil water temperature change (beyond the local coil loop itself). In large systems, a primary/secondary design with two-way valves is preferred, unless the primary equipment can handle the range of flow variation that will result without a secondary loop. Because chillers and boilers require that flow remain within a restricted range, the energy and cost savings that could accrue due to the two-way valve, variable volume system are difficult to achieve in small systems unless a two-pump, primary/secondary loop approach is employed. If this dual-loop approach is not used, the three-way valve method is required to maintain required boiler or chiller flow.

The location of the three-way valve at a coil must also be considered by the designer. Figure 6.16b shows the valve used downstream of the coil in a mixing, bypass mode. If a balancing valve is installed in the bypass line, and set to have the same pressure drop as the coil, the local coil loop will have the same pressure drop for both full and zero coil flow. However, at the valve mid-flow position, overall flow resistance is less,

TABLE 6.1 Quick sizing Chart for Control Valves

Cv	Steam Capacity, lb/h						Water Capacity, gal/min						
	Vacuum Return Systems[a]			Atmospheric Return Systems									
	2-psi Supply Press.	5-psi Supply Press.	10-psi Supply Press.	2-psi Supply Press.	5-psi Supply Press.	10-psi Supply Press.	Differential Pressure, psig						
	3.2-psi Press. Drop[b]	5.6-psi Press. Drop[b]	9.6-psi Press. Drop[b]	1.6-psi Press. Drop[b]	4.0-psi Press. Drop[b]	8.0-psi Press. Drop[b]	2	4	6	8	10	15	20
0.33	7.7	11.0	16.0	5.4	9.3	14.6	0.41	0.66	0.81	0.93	1.04	1.27	1.47
0.63	14.6	20.9	30.5	10.4	17.7	27.8	0.89	1.26	1.54	1.78	1.99	2.4	2.81
0.73	17.0	24.3	35.4	12	20.5	32.2	1.0	1.46	1.78	2.06	2.3	2.8	3.25
1.0	23.0	33.2	48.5	16.4	28	44	1.4	2.0	2.44	2.82	3.16	3.9	4.46
1.6	37.09	53.1	77.6	26.8	45	70.6	2.25	3.2	3.9	4.51	5.06	6.2	7.13
2.5	58.25	82.9	121.2	41.9	70.25	110.25	3.53	5.0	6.1	7.05	7.9	9.68	11.15
3.0	69.9	99.5	145.5	50.2	84.3	132.3	4.23	6.0	7.32	8.46	9.48	11.61	13.38
4.0	93.2	132.2	194.0	67	112.4	177.4	5.6	8.0	9.76	11.28	12.6	15.5	17.87
5.0	116.2	165.2	242.5	82.7	140.5	220.5	7.1	10.0	12.2	14.1	15.8	19.4	22.3
6.0	139	200	291.0	99	168	265	8.5	12.0	14.6	16.92	18.9	23.2	27.0
6.3	146	209	311.5	104	177	278	8.9	12.6	15.4	17.78	19.9	24.4	28.1
7.0	162	233	339.5	115	196	309	9.9	14.0	17.1	19.74	22.1	27.1	31
8.0	186.5	264.4	388.0	131.2	224.8	352.8	11.3	16.0	19.5	22.56	25.3	31.6	35.7
10.0	232	332	485.0	164	281	441	14.1	20	24.4	28.2	31.6	38.7	44.6
11.0	256	366	533.5	181	309	486	15.5	22	27	31.02	34.4	42.5	49
13.0	303	434	630.5	213.7	365.3	373.3	18.3	27	31.7	36.7	41.1	50.3	58
14.0	326	465	679.0	232	393	617	19.7	28	34	39	44	54	62
15.0	349.3	497.6	727.5	246	421.5	661.5	21.1	30	36.6	42.3	47.4	58	66.9
16.0	370.9	531	776.0	268	450	706	22.5	32	39	45.1	50.6	62	71.3
18.0	419	597	873.0	301	505	794	25	36	44	51	57	70	80
20.0	466	664	970.0	335	562	882	28	40	49	56	63	77	89
23.0	541	763	1,115	385	646	1,014	32	46	56	65	73	89	103
25.0	582.5	829	1,212	419	702.5	1,102.5	35.3	50	61	70.5	79	96.8	111.5
27.0	628.2	896	1,309	452.5	758.7	1,190.7	38.1	54	65.9	76.1	85.3	104.5	120.4
30.0	699	995	1,455	502	843	1,323	42.3	60	73.2	84.6	94.8	116.1	133.8
38.0	885	1,257	1,833	636	1,069	1,676	53	76	93	107	120	147	169
40.0	932	1,322	1,940	670	1,124	1,764	56	80	97.6	112.8	126	155	178.7
50.0	1,162	1,652	2,425	827	1,405	2,205	71	100	122	141	158	194	223
56.0	1,305	1,851	2,716	938	1,574	2,469	79	112	137	158	177	217	250

63.0	1,460	2,090	3,056	1,043	1,770	2,778	89	126	154	178	199	244	281
75.0	1,748	2,481	3,637	1,230	2,107	3,307	106	150	183	212	237	290	335
80.0	1,865	2,644	3,880	1,312	2,248	3,528	113	160	195	225.6	253	316	357
90.0	2,096	2,980	4,365	1,476	2,529	3,969	127	180	220	254	284	348	401
97.0	2,229	3,204	4,703	1,590	2,725	4,277	137	196	231	274	307	375	432
100.0	2,330	3,319	4,850	1,640	2,816	4,410	141	200	244	282	316	387	446
105.0	2,442	3,481	5,092	1,722	2,950	4,630	148	210	256	296	332	406	468
130.0	3,030	4,340	6,305	2,137	3,653	5,733	183	270	317	367	411	503	580
150.0	3,493	4,976	7,275	2,460	4,215	6,615	211	300	366	423	474	280	699
160.0	3,709	5,310	7,760	2,680	4,500	7,060	225	320	390	451	560	620	713
170.0	3,960	5,642	8,245	2,788	4,777	7,497	240	340	415	479	537	658	758
190.0	4,450	6,310	9,215	3,116	5,339	8,379	268	360	464	536	600	735	847
244.0	5,670	7,930	11,834	4,001	6,856	10,760	344	488	595	688	771	944	1,088
250.0	5,825	8,290	12,125	4,190	7,025	11,025	353	500	610	705	790	968	1,115
270.0	6,282	8,960	13,095	4,525	7,587	11,907	381	540	659	761	853	1,045	1,204
300.0	6,990	9,950	14,550	5,025	8,430	13,230	423	600	732	846	948	1,161	1,338
350.0	8,160	11,590	16,975	5,860	9,835	15,435	494	700	854	987	1,106	1,355	1,561
360.0	8,380	11,910	17,460	6,030	10,116	15,876	508	720	878	1,015	1,137	1,393	1,606
430.0	10,010	14,225	20,855	7,200	12,083	18,963	606	860	1,049	1,213	1,359	1,664	1,918
480.0	11,180	15,860	23,280	8,045	13,408	21,168	677	960	1,171	1,353	1,517	1,858	2,141
640.0	14,910	21,180	31,040	10,496	17,984	28,224	902	1,280	1,561	1,805	2,022	2,477	2,854
760.0	17,70	25,120	36,860	12,464	21,356	33,516	1,071	1,520	1,854	2,143	2,401	2,941	3,390
1,000.0	23,300	33,190	48,500	16,400	28,160	44,100	1,410	2,000	2,440	2,820	3,160	3,870	4,460
1,200.0	27,150	39,790	58,200	19,680	33,720	52,920	1,692	2,400	2,928	3,384	2,792	4,644	5,352
1,440.0	33,290	47,160	69,840	23,616	40,464	63,504	2,030	2,880	3,514	4,061	4,550	5,573	6,422

[a] Assuming a 4-in. through 8-in. vacuum.

[b] Pressure drop across fully open valve taking 80% of the pressure difference between supply and return main pressures.

Source: From Honeywell, Inc., *Engineering Manual of Automatic Control*, Honey well, Inc., Minneapolis, MN, 1988.

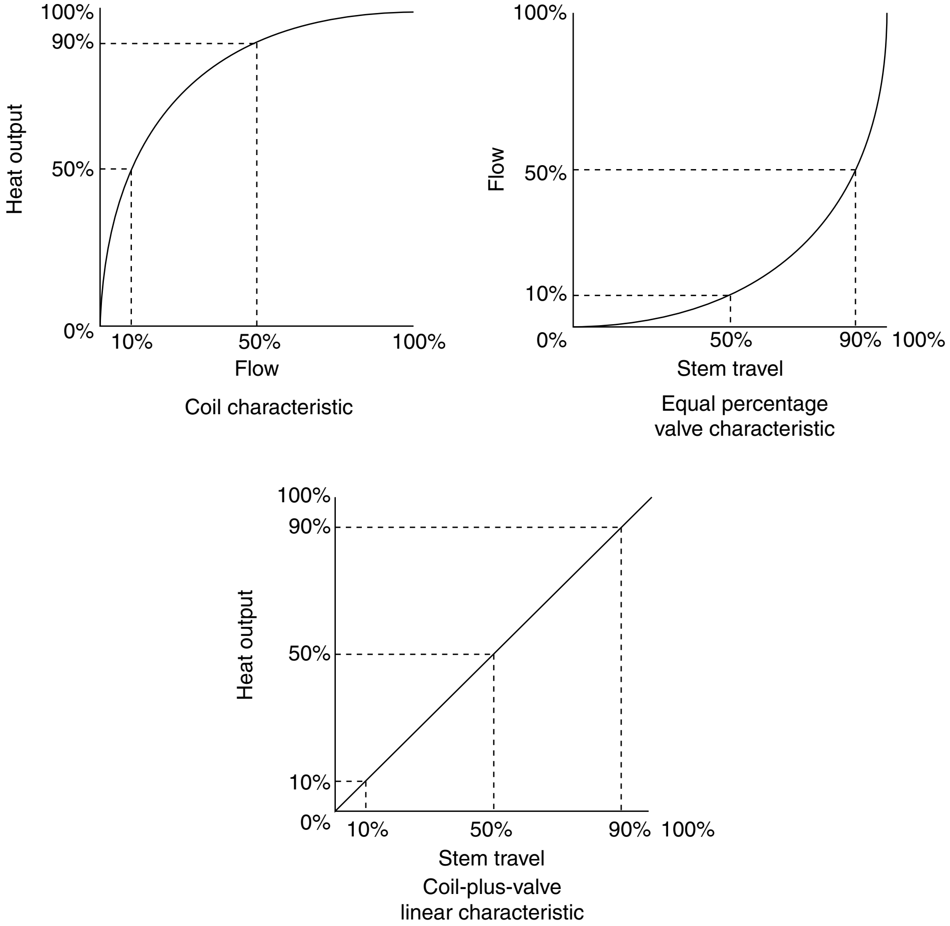

FIGURE 6.15 Heating coil, equal percentage valve, and combined coil + valve linear characteristic.

because two parallel paths are involved, and the total loop flow increases to 25% more than that at either extreme.

Alternatively, the three-way valve can also be used in a diverting mode, as shown in Figure 6.16c. In this arrangement, essentially the same considerations apply as for the mixing arrangement discussed earlier.[1] However, if a circulator (small pump) is inserted, as shown in Figure 6.16d, the direction of flow in the branch line changes and a mixing valve is used. The reason that pumped coils are used is that control is improved. With constant coil flow, the highly nonlinear coil characteristic shown in Figure 6.15 is reduced because the residence time of hot water in the coil is constant, independent of load. However, this arrangement appears to the external secondary loop the same as a two-way valve. As load is decreased, flow into the local coil loop also decreases. Therefore, the uniform secondary loop flow normally associated with three-way valves is not present unless the optional bypass is used.

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[1] A little-known disadvantage of three-way valve control has to do with the conduction of heat from a closed valve to a coil. For example, the constant flow of hot water through two ports of a closed three-way heating coil control valve keeps the valve body hot. Conduction from the closed, hot valve mounted close to a coil can cause sufficient air heating to actually decrease the expected cooling rate of a downstream cooling coil during the cooling season. Three-way valves have a second practical problem; installers often connect three-way valves incorrectly, given the choice of three pipe connections and three pipes to be connected. Both of these problems are avoided by using two-way valves.

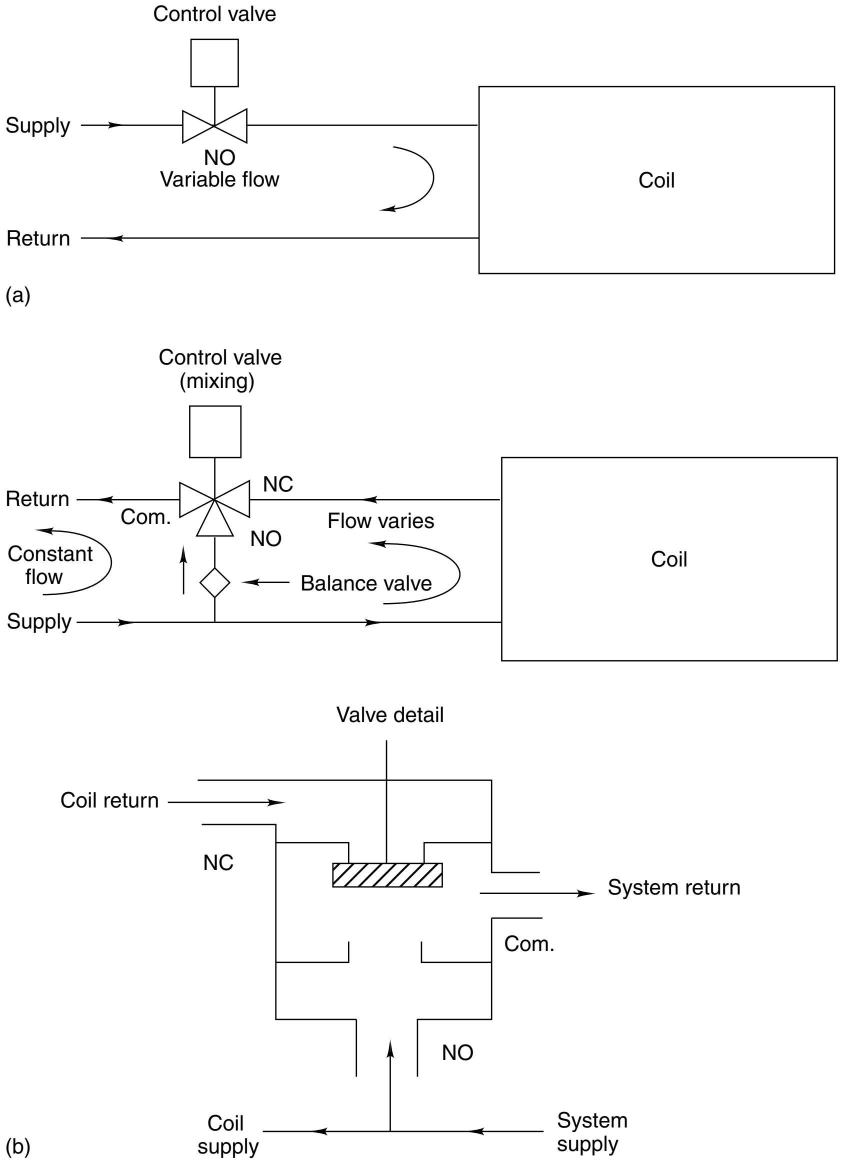

FIGURE 6.16 Various control valve piping arrangements (a) two-way valve; (b) three-way mixing valve; (c) three-way diverting valve; (d) pumped coil with three-way mixing valve.

For HVAC systems requiring precise control, high-quality control valves are required. The best controllers and valves are of "industrial quality." The additional cost for these valves compared to conventional building hardware results in more accurate control and longer lifetime.

6.4.2 Air Flow Control

Dampers are used to control airflow in secondary HVAC air systems in buildings. In this section, the characteristics of dampers used for flow control in systems where constant speed fans are involved are discussed. Figure 6.17 shows cross sections of the two common types of dampers used in commercial buildings. Parallel blade dampers use blades that all rotate in the same direction. They are most often

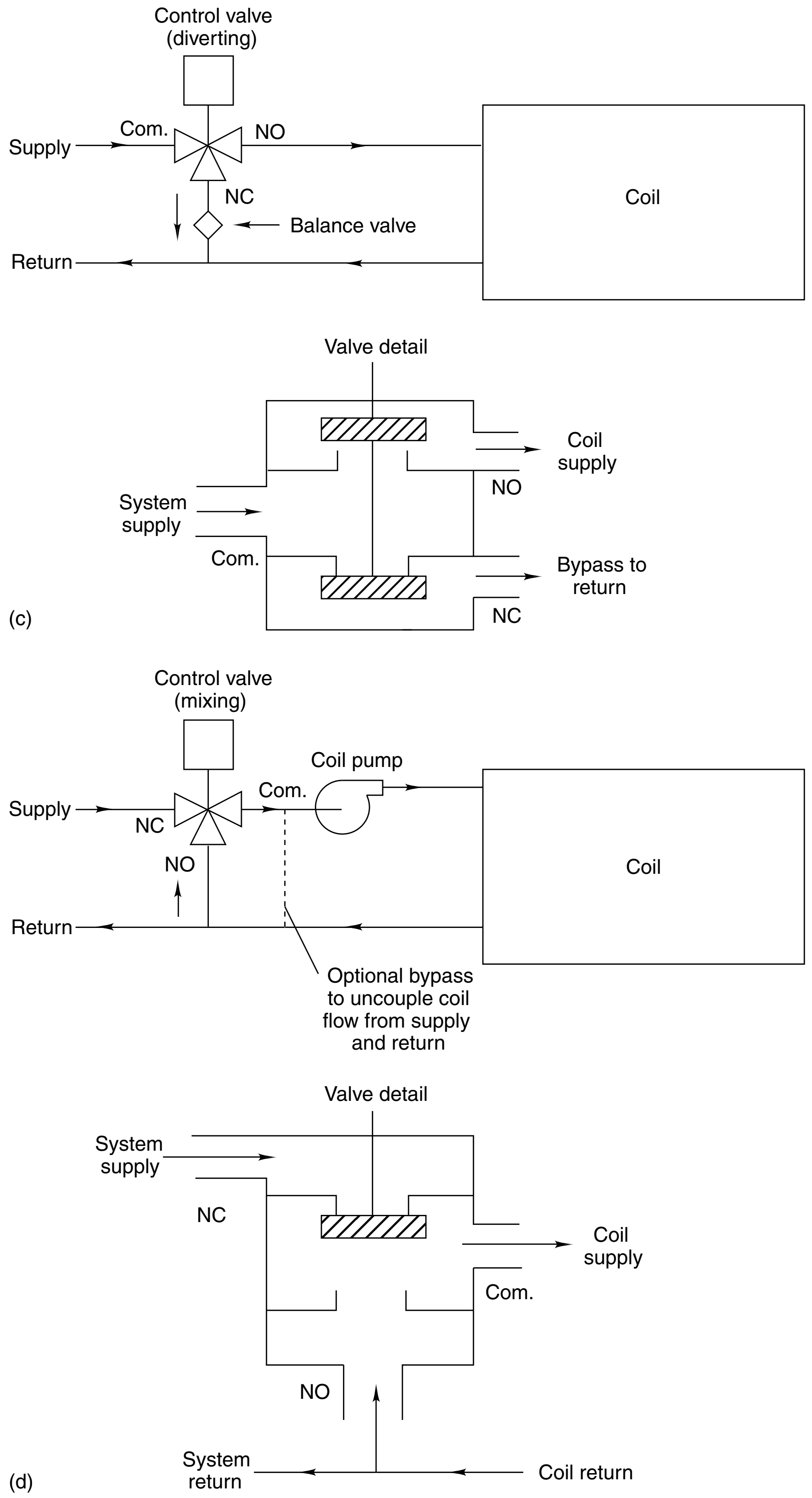

FIGURE 6.16 (*continued*)

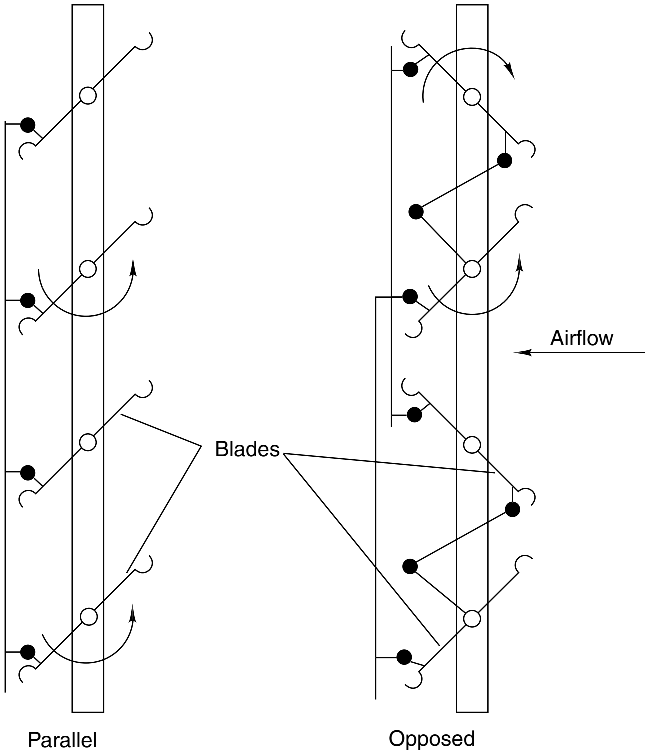

FIGURE 6.17 Diagram of parallel and opposed blade dampers.

applied to two position locations—open or closed. Use for flow control is not recommended. The blade rotation changes airflow direction, a characteristic that can be useful when airstreams at different temperatures are to be effectively blended.

Opposed blade dampers have adjacent counter-rotating blades. Airflow direction is not changed with this design, but pressure drops are higher than for parallel blading. Opposed blade dampers are preferred for flow control. Figure 6.18 shows the flow characteristics of these dampers to be closer to the desired linear behavior. The parameter α on the curves is the ratio of system pressure drop to fully open damper pressure drop.

A common application of dampers controlling the flow of outside air uses two sets in a face and bypass configuration as shown in Figure 6.19. For full heating, all air is passed through the coil and the bypass dampers are closed. If no heating is needed in mild weather, the coil is bypassed (for minimum flow resistance and fan power cost, flow through fully open face and bypass dampers can be used if the preheat coil water flow is shut off). Between these extremes, flow is split between the two paths. The face and bypass dampers are sized so that the pressure drop in full bypass mode (damper pressure drop only) and full heating mode (coil plus damper pressure drop) is the same.

6.5 Example HVAC Control Systems

Several widely used control configurations for specific tasks are described in this section. These have been selected from the hundreds of control system configurations that have been used for buildings. The goal of this section is to illustrate how control components described above are assembled into systems, and what design considerations are involved. For a complete overview of HVAC control system configurations see Honeywell (1988), Grimm and Rosaler (1990), Sauer, Howell, and Coad (2001), ASHRAE

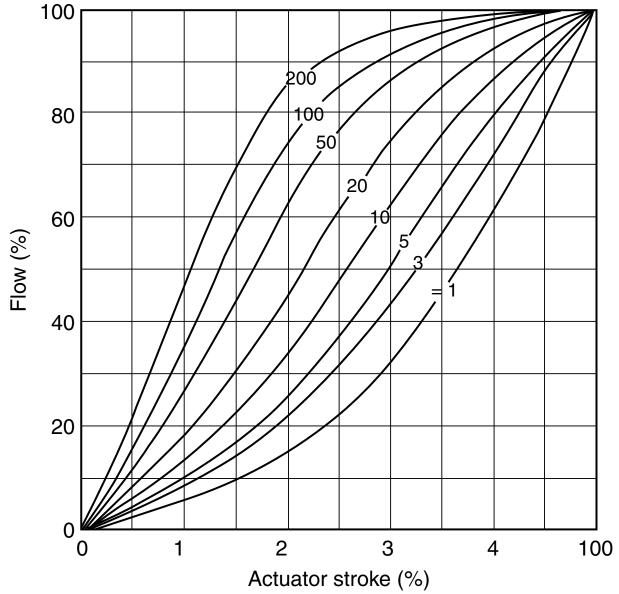

FIGURE 6.18 Flow characteristics of opposed blade dampers. The parameter α is the ratio of system resistance (not including the damper) to damper resistance. An approximately linear damper characteristic is achieved if this ratio is about 10 for opposed blade dampers.

(2002, 2003, 2004), and Tao and Janis (2005). The illustrative systems in this section are drawn in part from the first of these references.

In this section, seven control systems in common use will be discussed. Each system will be described using a schematic diagram, and its operation and key features will be discussed in the accompanying text.

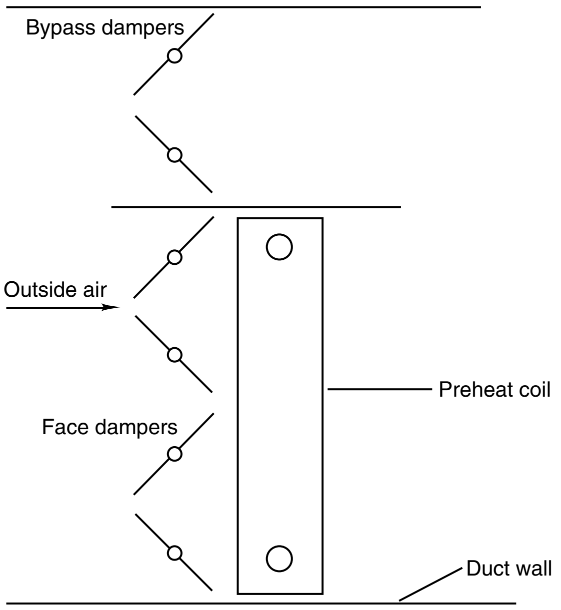

FIGURE 6.19 Face and bypass dampers used for preheating coil control.

6.5.1 Outside Air Control

Figure 6.20 shows a system for controlling outside and exhaust air from a central air handling unit equipped for economizer cooling when available. In this and the following diagrams, the following symbols are used:

C—cooling coil
DA—discharge air (supply air from fan)
DX—direct-expansion coil
E—damper controller
EA—exhaust air
H—heating coil
LT—low-temperature limit sensor or switch, must sense the lowest temperature in the air volume being controlled
M—motor or actuator (for damper or valve), variable speed drive
MA—mixed air
NC—normally closed
NO—normally open
OA—outside air
PI—proportional plus integral controller
R—relay
RA—return air
S—switch
SP—static pressure sensor used in VAV systems

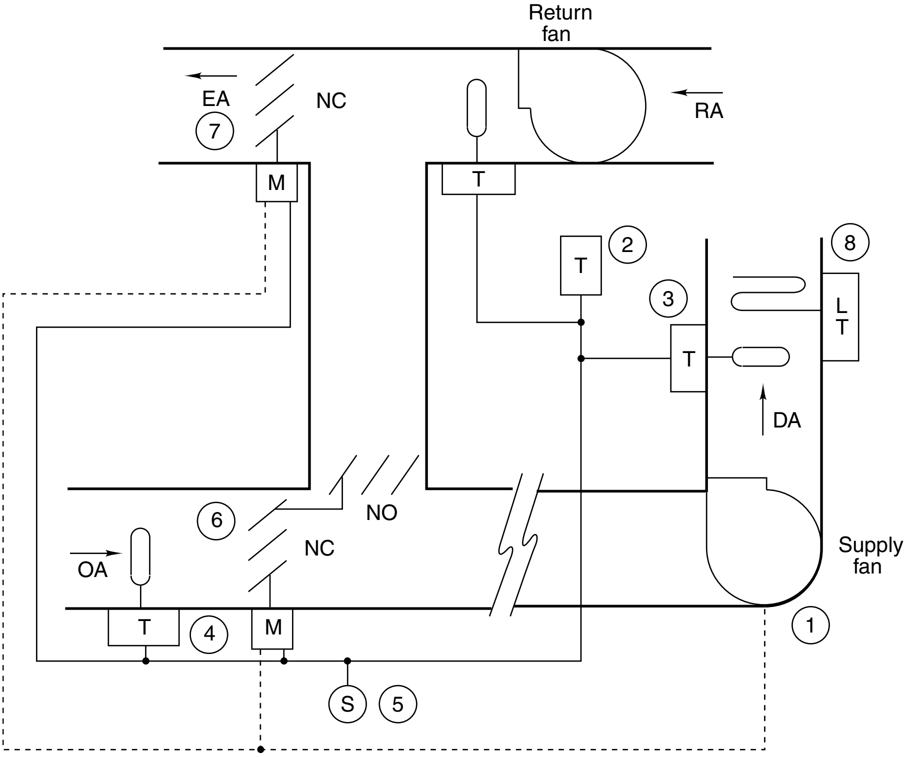

FIGURE 6.20 Outside-air-control system with economizer capability.

T—temperature sensor; must be located to read the average temperature representative of the air volume being controlled

This system is able to provide the minimum outside air during occupied periods; to use outdoor air for cooling when appropriate, by means of a temperature-based economizer cycle; and to operate fans and dampers under all conditions. The numbering system used in the figure indicates the sequence of events as the air handling system begins operation after an off period:

1. The fan control system turns on when the fan is turned on. This may be by a clock signal or a low- or high-temperature space condition.
2. The space temperature signal determines whether the space is above or below the setpoint. If above, the economizer feature will be activated if the OA temperature is below the upper limit for economizer operation, and will control the outdoor and mixed air dampers. If below, the outside air damper is set to its minimum position.
3. The discharge air PI controller controls both sets of dampers (OA/RA and EA) to provide the desired mixed air temperature.
4. When the outdoor temperature rises above the upper limit for economizer operation, the outdoor air damper is returned to its minimum setting.
5. Switch S is used to set the minimum setting on outside and exhaust air dampers manually. This is ordinarily done only once, during building commissioning and flow testing.
6. When the supply fan is off, the outdoor air damper returns to its NC position and the return air damper returns to its NO position.
7. When the supply fan is off, the exhaust damper also returns to its NC position.
8. Low temperature sensed in the duct will initiate a freeze-protect cycle. This may be as simple as turning on the supply fan to circulate warmer room air. Of course, the OA and EA dampers remain tightly closed during this operation.

6.5.2 Heating Control

If the minimum air setting is large in the preceding system, the amount of outdoor air admitted in cold climates may require preheating. Figure 6.21 shows a preheating system using face and bypass dampers. (A similar arrangement is used for direct-expansion [DX] cooling coils.) The equipment shown is installed upstream of the fan in Figure 6.20. This system operates as follows:

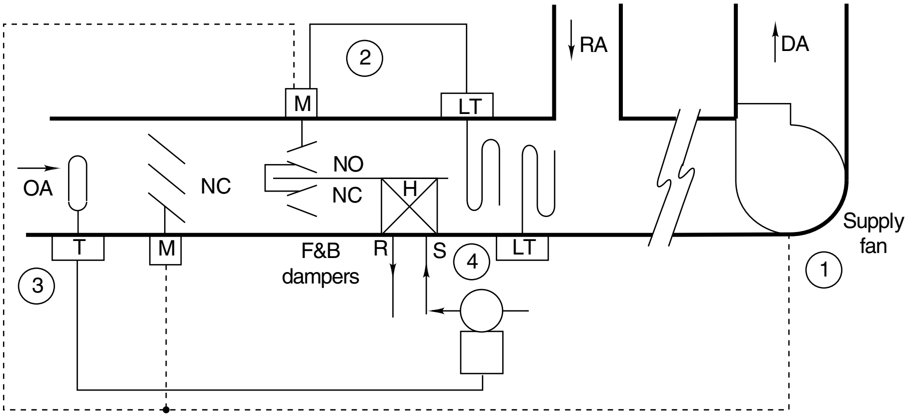

FIGURE 6.21 Preheat control system. Counter flow of air and hot water in the preheat coil results in the highest heat transfer rate.

1. The preheat subsystem control is activated when the supply fan is turned on.
2. The preheat PI controller senses temperature leaving the preheat section. It operates the face and bypass dampers to control the exit air temperature between 45 and 50°F.
3. The outdoor air sensor and associated controller controls the water valve at the preheat coil. The valve may be either a modulating valve (better control) or an on–off valve (less costly).
4. The low-temperature sensors (LTs) activate coil freeze protection measures, including closing dampers and turning off the supply fan.

Note that the preheat coil (as well as all other coils in this section) is connected so that the hot water (or steam) flows counter to the direction of airflow. Counter flow provides a higher heating rate for a given coil than does parallel flow. Mixing of heated and cold bypass air must occur upstream of the control sensors. Stratification can be reduced by using sheet metal air blenders or by propeller fans in the ducting. The preheat coil should be located in the bottom of the duct. Steam preheat coils must have adequately sized traps and vacuum breakers to avoid condensate buildup that could lead to coil freezing at light loads.

The face and bypass damper approach enables air to be heated to the required system supply temperature without endangering the heating coil. (If a coil were to be as large as the duct—no bypass area—it could freeze when the hot water control valve cycles open and closed to maintain discharge temperature.) The designer should consider pumping the preheat coil as shown in Figure 6.19d to maintain water velocity above the 3 ft./s needed to avoid freezing. If glycol is used in the system, the pump is not necessary, but heat transfer will be reduced.

During winter in heating climates, heat must be added to the mixed air stream to heat the outside air portion of mixed air to an acceptable discharge temperature. Figure 6.22 shows a common heating subsystem controller used with central air handlers. (It is assumed that the mixed air temperature is kept above freezing by action of the preheat coil, if needed.) This system has the added feature that coil discharge temperature is adjusted for ambient temperature because the amount of heat needed decreases with increasing outside temperature. This feature, called *coil discharge reset*, provides better control and can reduce energy consumption. The system operates as follows:

1. During operation the discharge air sensor and PI controller controls the hot water valve.
2. The outside air sensor and controller resets the setpoint of the discharge air PI controller up as ambient temperature drops.

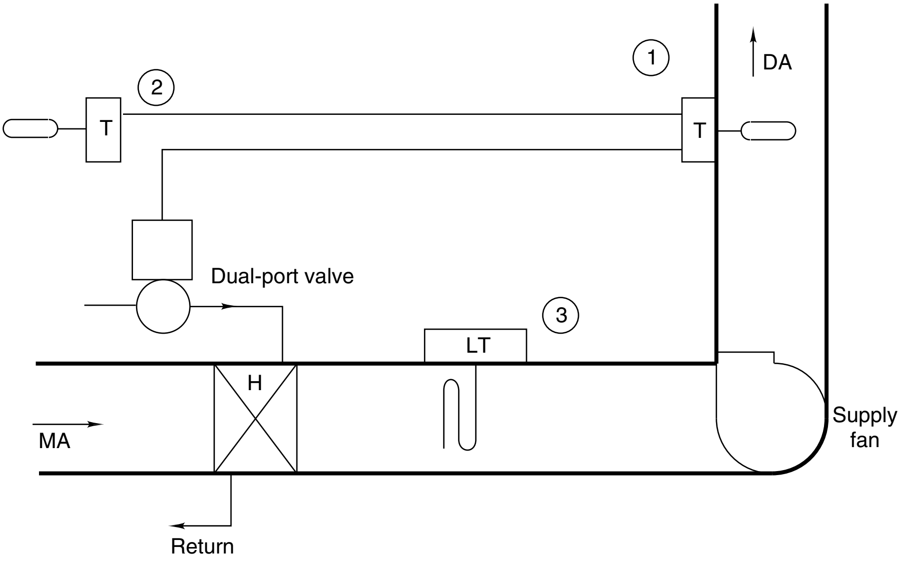

FIGURE 6.22 Heating-coil control subsystem using two-way valve and optional reset sensor.

3. Under sensed low-temperature conditions, freeze-protection measures are initiated as discussed earlier.

Reheating at zones in VAV or other systems uses a system similar to that just discussed. However, boiler water temperature is reset and no freeze protection is normally included. The air temperature sensor is the zone thermostat for VAV reheat, not a duct temperature sensor.

6.5.3 Cooling Control

Figure 6.23 shows the components in a cooling coil control system for a single-zone system. Control is similar to that for the heating coil discussed above, except that the zone thermostat (not a duct temperature sensor) controls the coil. If the system were a central system serving several zones, a duct sensor would be used. Chilled water supplied to the coil partially bypasses and partially flows through the coil, depending on the coil load. The use of three- and two-way valves for coil control has been discussed in detail previously. The valve NC connection is used as shown so that valve failure will not block secondary loop flow.

Figure 6.24 shows another common cooling coil control system. In this case the coil is a direct-expansion (DX) refrigerant coil and the controlled medium is refrigerant flow. DX coils are used when precise temperature control is not required because the coil outlet temperature drop is large whenever refrigerant is released into the coil because refrigerant flow is not modulated; it is most commonly either on or off. The control system sequences as follows:

1. The coil control system is energized when the supply fan is turned on.
2. The zone thermostat opens the two-position refrigerant valve for temperatures above the setpoint and closes it in the opposite condition.
3. At the same time, the compressor is energized or de-energized. The compressor has its own internal controls for oil control and pumpdown.
4. When the supply fan is off, the refrigerant solenoid valve returns to its NC position and the compressor relay to its NO position.

At light loads, bypass rates are high and ice may build up on coils. Therefore, control is poor at light loads with this system.

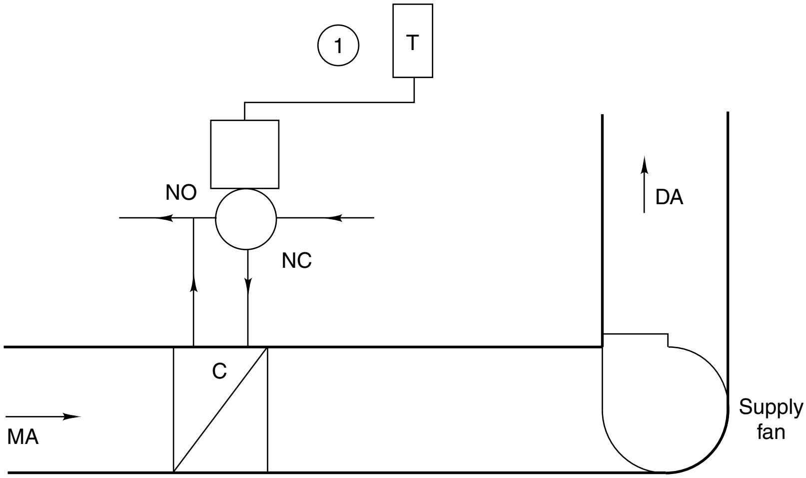

FIGURE 6.23 Cooling-coil control subsystem using three-way diverting valve.

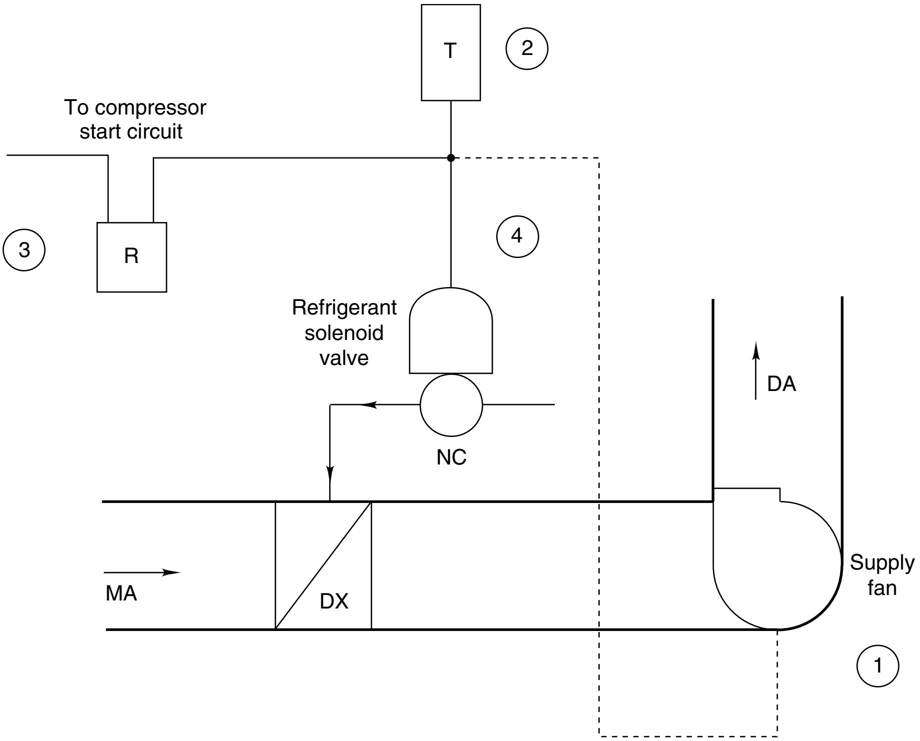

FIGURE 6.24 DX cooling coil control subsystem (on-off control).

6.5.4 Complete Systems

The preceding five example systems are actually control subsystems that must be integrated into a single control system for the HVAC system's primary and secondary systems. In the remainder of this section, two complete HVAC control systems widely used in commercial buildings will be briefly described. The first is a constant volume system, and the second is a VAV system.

Figure 6.25 shows a constant volume, central air-handling system equipped with supply and return fans, heating and cooling coils, and economizer for a single-zone application. If the system were to be used for multiple zones, the zone thermostat shown would be replaced by a discharge air temperature sensor. This constant volume system operates as follows:

1. When the fan is energized, the control system is activated.
2. The minimum outside air setting is set (usually only once, during commissioning, as described above).
3. The OA temperature sensor supplies a signal to the damper controller.
4. The RA temperature sensor supplies a signal to the damper controller.
5. The damper controller positions the dampers to use outdoor or return air, depending on which is cooler.
6. The mixed-air low-temperature controller controls the outside air dampers to avoid excessively low-temperature air from entering the coils. If a preheating system were included, this sensor would control it.
7. The space temperature sensor resets the coil discharge air PI controller.
8. The discharge air controller controls the
   a. Heating coil valve
   b. Outdoor air damper

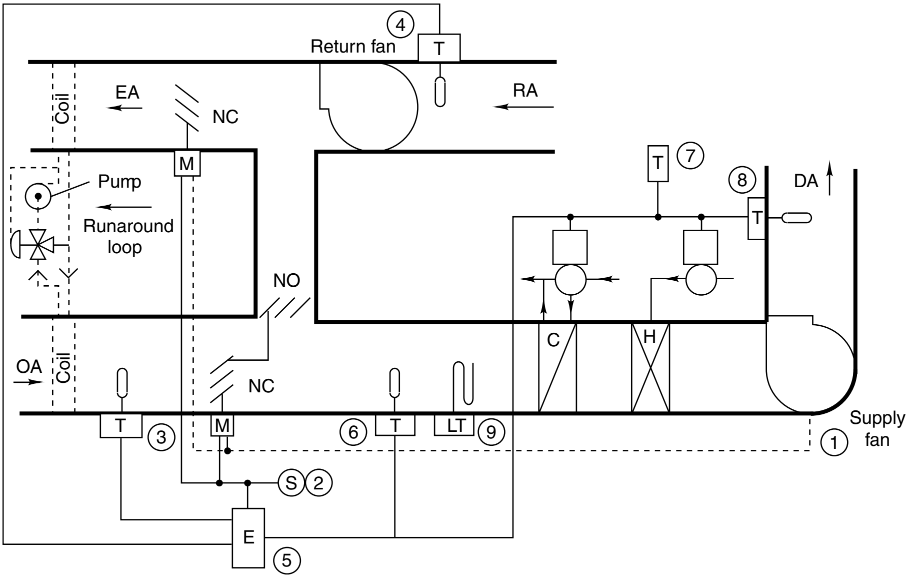

FIGURE 6.25 Control for a complete, constant volume HVAC system. Optional runaround heat recovery system is shown to left in dashed lines.

   c. Exhaust air damper
   d. Return air damper
   e. Cooling coil valve (after the economizer cycle upper limit is reached)
9. The low-temperature sensor initiates freeze protection measures as described previously.

A method for reclaiming either heating or cooling energy is shown by dashed lines on the left side of Figure 6.25. This so-called “runaround” system extracts energy from exhaust air and uses it to precondition outside air. For example, the heating season exhaust air may be at 75°F, while outdoor air is at 10°F. The upper coil in the figure extracts heat from the 75°F exhaust and transfers it through the lower coil to the 10°F intake air. To avoid icing of the air intake coil, the three-way valve controls this coil’s liquid inlet temperature to a temperature above freezing. In heating climates, the liquid loop should also be freeze protected with a glycol solution. Heat reclaiming systems of this type can also be effective in the cooling season, when outdoor temperatures are well above indoor temperatures.

A VAV system has additional control features including a motor speed control (or inlet vanes in some older systems) and a duct static pressure control. Figure 6.26 shows a VAV system serving both perimeter and interior zones. It is assumed that the core zones always require cooling during the occupied period. The system shown has a number of options, and does not include every feature present in all VAV systems. However, it is representative of VAV design practice. The sequence of operation during the heating season is as follows:

1. When the fan is energized, the control system is activated. Prior to activation, during unoccupied periods the perimeter zone baseboard heating is under control of room thermostats.
2. Return and supply fan interlocks are used to prevent pressure imbalances in the supply air ductwork.
3. The mixed air sensor controls the outdoor air dampers or preheat coil (not shown) to provide proper coil air inlet temperature. The dampers will typically be at their minimum position at about 40°F.
4. The damper minimum position controls the minimum outdoor airflow.

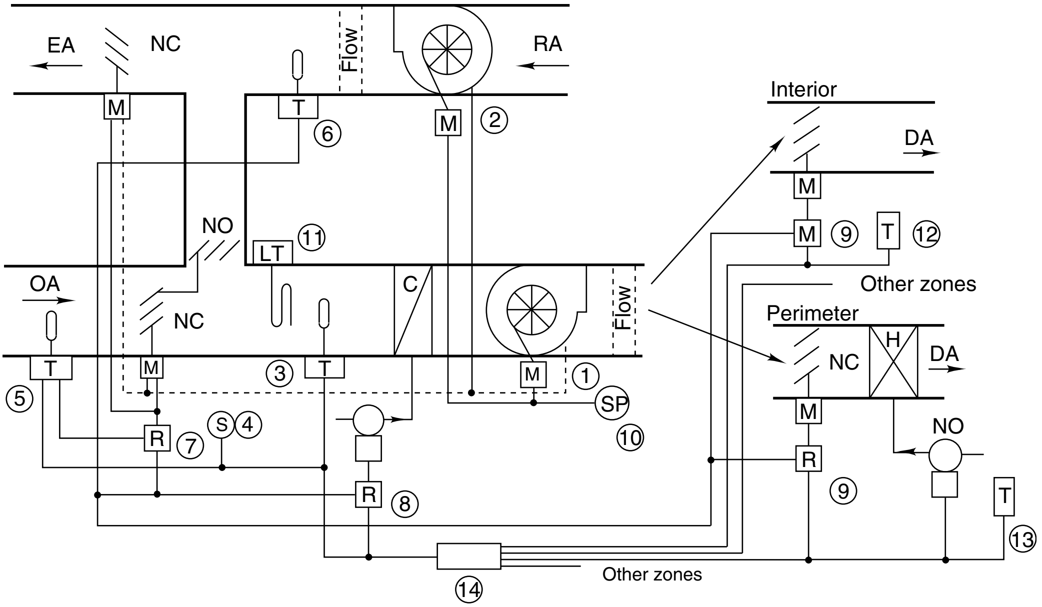

FIGURE 6.26 Control for complete, VAV system. Optional supply and return flow stations shown with dashed lines.

5. As the upper limit for economizer operation is reached, the OA dampers are returned to their minimum position.
6. The return air temperature is used to control the morning warmup cycle after night setback (option present only if night setback is used).
7. The outdoor air damper is not permitted to open during morning warmup, by action of the relay shown.
8. Likewise, the cooling coil valve is de-energized (NC) during morning warmup.
9. All VAV box dampers are moved full open during morning warmup by action of the relay override. This minimizes warmup time. Perimeter zone coils and baseboard units are under control of the local thermostat.
10. During operating periods, the PI static pressure controller controls both supply and return fan speeds (or inlet vane positions) to maintain approximately 1.0 in. WG of static pressure at the pressure sensor location (or, optionally, to maintain building pressure). An additional pressure sensor (not shown) at the supply fan outlet will shut down the fan if fire dampers or other dampers should close completely and block airflow. This sensor overrides the duct static pressure sensor shown.
11. The low-temperature sensor initiates freeze-protection measures.
12. At each zone, room thermostats control VAV boxes (and fans, if present); as zone temperature rises the boxes open more.
13. At each perimeter zone room, thermostats close VAV dampers to their minimum settings and activate zone heat (coil or perimeter baseboard) as zone temperature falls.
14. The controller, using temperature information for all zones (or at least for enough zones to represent the characteristics of all zones), modulates outdoor air dampers (during economizer operation) and the cooling control valve (above the economizer cycle cutoff), to provide air sufficiently cooled to maintain acceptable zone humidity and meet the load of the warmest zone.

The duct static pressure controller is critical to the proper operation of VAV systems. The static pressure controller must be of PI design because a proportional-only controller would permit duct pressure to drift upward as cooling loads drop due to the unavoidable offset in P-type controllers. In addition, the control system should position inlet vanes (if present) closed during fan shutdown, to avoid overloading on restart.

Return fan control is best achieved in VAV systems by an actual flow measurement in supply and return ducts as shown by dashed lines in the figure. The return airflow rate is the supply rate less local exhausts (fume hoods, toilets, etc.) and exfiltration needed to pressurize the building.

VAV boxes are controlled locally, assuming that adequate duct static pressure exists in the supply duct and that supply air is at an adequate temperature to meet the load (this is the function of the controller described in item 11.14). Figure 6.27 shows a local control system used with a series-type, fan-powered VAV box. This particular system delivers a constant flow rate to the zone by action of the airflow controller, to assure proper zone air distribution. Primary air varies with cooling load, as shown in the lower part of the figure. Optional reheating is provided by the coil shown.

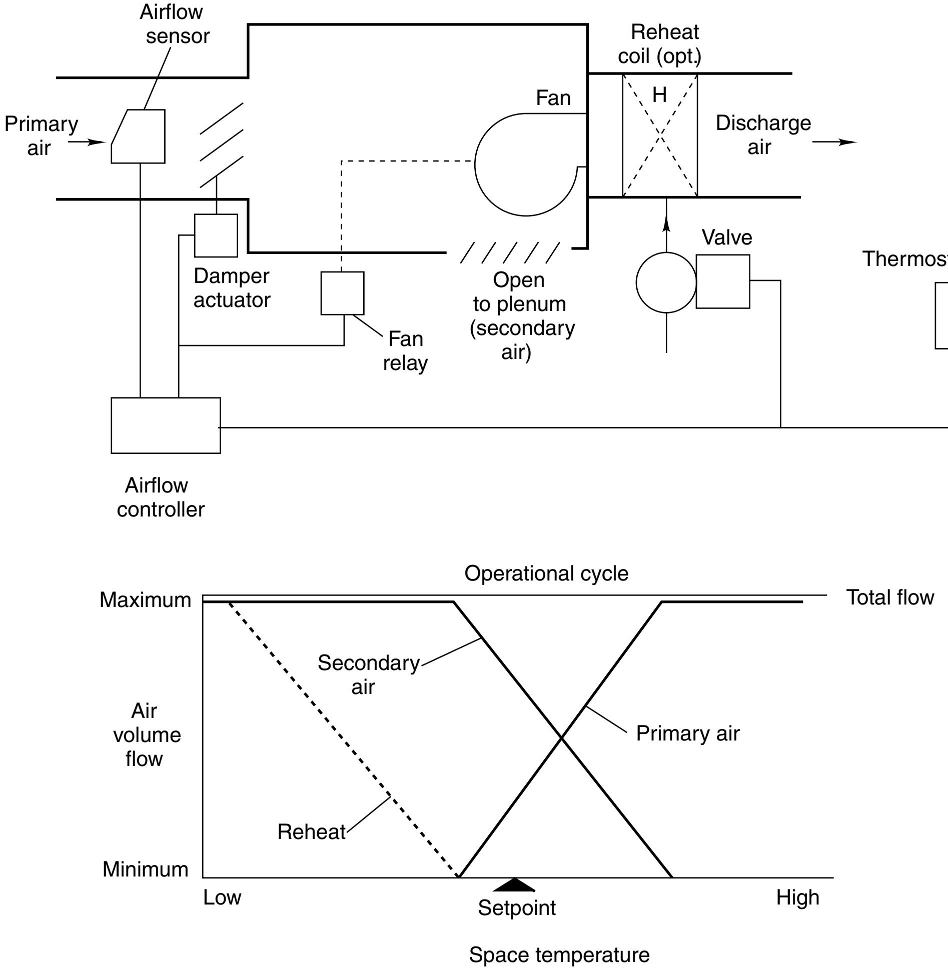

FIGURE 6.27 Series type, fan powered VAV box control subsystem and primary flow characteristic. The total box flow is constant at the level identified as "maximum" in the figure. The difference between primary and total air flow is secondary air recirculated through the return air grille. Optional reheat coil requires air flow shown by dashed line.

6.5.5 Other Systems

This section has not covered the control of central plant equipment such as chillers and boilers. Most primary system equipment controls are furnished with the equipment and as such do not offer much flexibility to the designer. However, Braun et al. (1989) have shown that considerable energy savings can be made by properly sequencing cooling tower stages on chiller plants, and by properly sequencing chillers themselves in multiple chiller plants.

Fire and smoke control are important for life safety in large buildings. The design of smoke control systems is controlled by national codes. The principal goal is to eliminate smoke from the zones where it is present, while keeping adjacent zones pressurized to prevent smoke infiltration. Some components of space conditioning systems (e.g., fans) can be used for smoke control, but HVAC systems are generally not designed to be smoke control systems.

Electrical systems are primarily the responsibility of the electrical engineer on a design team. However, HVAC engineers must make sure that the electrical design accommodates the HVAC control system. Interfaces between the two occur where the HVAC controls activate motors on fans or chiller compressors, pumps, electrical boilers, or other electrical equipment.

In addition to electrical specifications, the HVAC engineer often conveys electrical control logic using a ladder diagram. An example, for the control of the supply and return fans in a central system, is shown in Figure 6.28. The electrical control system, shown at the bottom, operates on low voltage (24 or 48 VAC) from the control transformer shown. The supply fan is started manually by closing the "start" switch. This activates the motor starter coil labeled 1M, thereby closing the three contacts labeled 1M in the supply fan circuit. The fourth 1M contact (in parallel with the start switch) holds the starter closed after the start button is released.

The hand-off auto switch is typical, and allows both automatic and manual operation of the return fan. When switched to the "hand" position, the fan starts. In the "auto" position, the fans will operate only when the adjacent contacts 3M are closed. Either of these actions activates the relay coil 2M, which in turn closes the three 2M contacts in the return fan motor starter. When either fan produces actual airflow, a flow switch is closed in the ducting, thereby completing the circuit to the pilot lamps L. The fan motors are protected by fuses and thermal overload heaters. If motor current draw is excessive, the heaters shown in the figure produce sufficient heat to open the normally closed thermal overload contacts.

FIGURE 6.28 The Brooke Army Medical Center (BAMC) in San Antonio, Texas.

This example ladder diagram is primarily illustrative, and is not typical of an actual design. In a fully automatic system, both fans would be controlled by 3M contacts actuated by the HVAC control system. In a fully manual system, the return fan would be activated by a fifth 1M contact, not by the 3M automatic control system.

6.6 Commissioning and Operation of Control Systems

This chapter emphasizes the importance of making sound decisions in the design of HVAC control systems. It is also extremely important that the control system be commissioned and used properly. The design process requires many assumptions about the building and its use. The designer must be sure that the systems will provide comfort under extreme conditions, and the sequence of design decisions and construction decisions often leads to systems that are substantially oversized. Operation at loads far below design conditions is generally much less efficient than at larger loads. Normal control practice can be a major contributor to this inefficiency. For example, it is quite common to see variable volume air handler systems operating at minimum flow as constant volume systems almost all the time, due to design flows that are sometimes twice as large as the maximum flow used in the building.

Thus, it is very important that following construction, the control system and the rest of the HVAC system be commissioned. This process (ASHRAE 2005) normally seeks to ensure that the control system operates according to design intent. This is really a minimum requirement to be sure that the system functions as designed. However, after construction, the control system setup can be modified to meet the loads actually present in the building, and to fit the way the building is actually being used, rather than basing these decisions on the design assumptions. If the VAV system is designed for more flow than is required, minimum flow settings of the terminal boxes can be reduced below the design value, ensuring that the system will operate in the VAV mode most of the time. Numerous other adjustments may be made as well. Such adjustments, commonly made during the version of commissioning known as *Continuous Commissioning*®[2](CC®), can frequently reduce the overall building energy use by 10% or more (Liu, Claridge, and Turner 2002). If the process is applied to an older building where control practices have drifted away from design intent and undetected component failures have further eroded system efficiency, energy savings often exceed 20% (Claridge et al. 2004).

6.6.1 Control Commissioning Case Study

A case study in which this process was applied to a major Army hospital facility located in San Antonio, Texas is reported in Zhu et al. (2000a, 2000b, 2000c). The Brooke Army Medical Center (BAMC) was a relatively new facility when the CC® process was begun. The facility was operated for the Army by a third-party company, and it was operated in accordance with the original design intent.

BAMC is a large, multifunctional medical facility with a total floor area of 1,349,707 ft.^{2}. The complex includes all the normal inpatient facilities, as well as outpatient and research areas. The complex is equipped with a central energy plant, which has four 1,200 ton water-cooled electric chillers. Four primary pumps (75 hp each) are used to pump water through the chillers. Two secondary pumps (200 hp each) equipped with VFDs supply chilled water from the plant to the building entrance. Fourteen chilled water risers equipped with 28 pumps totaling 557 hp are used to pump chilled water to all of the AHUs and small fan coil units. All of the chilled water riser pumps are equipped with VFDs. There are four natural gas-fired steam boilers in this plant. The maximum output of each boiler is 20 MMBtu/h. Steam is supplied to each building, where heating water was generated, at 125 psi (prior to commissioning).

There are 90 major AHUS serving the whole complex, with a total fan power of 2570 hp. VFDs are installed on 65 AHUs while the others are constant volume systems. There are 2,700 terminal boxes in the

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[2] Continuous Commissioning and CC are registered trademarks of the Texas Engineering Experiment Station.

complex, of which 27% are dual duct variable volume (DDVAV) boxes, 71% are dual duct constant volume (DDCV) boxes, and 2% are single duct variable volume (SDVAV) boxes.

The HVAC systems (chillers, boilers, AHUs, pumps, terminal boxes and room conditions) are controlled by a DDC control system. Individual controller-field panels are used for the AHUs and water loops located in the mechanical rooms. The control program and parameters can be changed by either the central computers or the field panels.

6.6.1.1 Design Conditions

The design control program was being fully utilized by the EMCS. It included the following features:

1. Hot deck reset control for AHUS
2. Cold deck reset during unoccupied periods for some units
3. Static pressure reset between high and low limits for VAV units
4. Hot water supply temperature control with reset schedule
5. VFD control of chilled water pumps with ΔP setpoint (no reset schedule)
6. Terminal box level control and monitoring

It was also determined that the facility was being well maintained by the facility operator, in accordance with the original design intent. The building is considered energy efficient for a large hospital complex.

The commissioning activities were performed at the terminal box level, AHU level, loop level and central plant level. Several different types of improved operation measures and energy solutions were implemented in different HVAC systems, due to the actual function and usage of the areas and rooms. Each measure will be discussed briefly, starting with the air-handling units.

6.6.1.2 Optimization of AHU Operation

EMCS trending, complemented by site measurements and use of short-term data loggers, found that many supply fans operated above 90% of full speed most of the time. Static pressures were much higher than needed. Wide room temperature swings due to AHU shutoff led to hot and cold complaints in some areas. Through field measurements and analysis, the following possible means of improving the operation of the two AHUs were identified.

- Improve zone air balancing and determine new static pressure setpoints for VFDs
- Optimize the cold deck temperature setpoints with reset schedules
- Optimize the hot deck temperature reset schedules
- Improve control of outside air intake and relief dampers during unoccupied periods to reduce ventilation during these periods
- Optimize time schedule for fans to improve room conditions
- Improve the preheat temperature setpoint to avoid unnecessary preheating

Implementation of these measures improved comfort and reduced heating, cooling, and electric use.

6.6.1.3 Optimization at the Terminal Box Level

Field measurements showed that many VAV boxes had minimum flow settings that were higher than necessary, and that some boxes were unable to supply adequate hot air due to specific control sequences. New control logic was developed that increased hot air capacity by 30% on average, in the full heating mode, and reduced simultaneous heating and cooling. During unoccupied periods, minimum flow settings on VAV boxes were reduced to zero and flow settings were reduced in constant volume boxes.

During commissioning, it was found that some terminal boxes could not provide the required airflow either before or after the control program modification. Specific problems were identified in about 200 boxes, with most being high flow resistance due to kinked flex ducts.

6.6.1.4 Water Loop Optimization

There are 14 chilled water risers, equipped with 28 pumps, which provide chilled water to the entire complex. During the commissioning assessment phase, the following were observed:

- All the riser pumps were equipped with VFDs, which were running at 70%–100% of full speed.
- All of the manual balancing valves on the risers were only 30%–60% open.
- The ΔP sensor for each riser was located 10–20 ft. from the far-end coil of the AHU on the top floor.
- Differential pressure setpoints for each riser ranged from 13 to 26 psi.
- There was no control valve on the return loop.
- Although most of the cold deck temperatures were holding well, there were 13 AHUs whose cooling coils were 100% open, but which could not maintain cold deck temperature setpoints.

Because the risers are equipped with VFDs, traditional manual balancing techniques are not appropriate. All the risers were rebalanced by initially opening all of the manual balancing valves. The actual pressure requirements were measured for each riser, and it was determined that the ΔP for each riser could be reduced significantly. Pumping power requirements were reduced by more than 40%.

6.6.1.5 Central Plant Measures

1. *Boiler System*: Steam pressure was reduced from 125 psi to110 psi, and one boiler operated instead of two during summer and swing seasons.
2. *Chilled Water Loop*: Before the commissioning, the blending valve separating the primary and secondary loops at the plant was 100% open. The primary and secondary pumps were both running. The manual valves were partially open for the secondary loop, although the secondary loop pumps are equipped with VFDs. After the commissioning assessment and investigations, the following were implemented:

- Open the manual valves for the secondary loop
- Close the blending stations
- Shut down the secondary loop pumps

As a result, the primary loop pumps provide required chilled water flow and pressure to the building entrance for most of the year, and the secondary pumps stay offline most of the time. The operator drops the online chiller numbers according to the load conditions, and the minimum chilled water flow can be maintained to the chillers. At the same time, the chiller efficiency is increased.

6.6.1.6 Results

For the fourteen-month period following initial CC® implementation, measured savings were nearly $410,000, or approximately $30,000/month, for a reduction in both electricity and gas use of about 10%. The contracted cost to meter, monitor, commission, and provide a year's follow-up services was less than $350,000. This cost does not include any time for the facilities operating staff who repaired kinked flex ducts, replaced failed sensors, implemented some of the controls and subroutines, and participated in the commissioning process.

6.6.2 Commissioning Existing Buildings

The savings achieved from commissioning HVAC systems in older buildings are even larger. In addition to the opportunities for improving efficiency similar to those in new buildings, opportunities come from:

- Control changes that have been made to "solve" problems, often resulting in lower operating efficiency

- Component failures that compromise efficiency without compromising comfort
- Deferred maintenance that lowers efficiency

Mills et al. (2004 and 2005) surveyed 150 existing buildings that had been commissioned and found median energy cost savings of 15%, with savings in one-fourth of the buildings exceeding 29%. Over 60% of the problems corrected were control changes, and another 20% were related to faulty components that prevented proper control. This suggests that relatively few control systems actually achieve the efficiency they are capable of providing.

6.7 Advanced Control System Design Topics: Neural Networks

Neural networks offer considerable opportunity to improve the control possible in standard PID systems. This section provides a short introduction to this novel approach to control.

6.7.1 Neural Network Introduction

An artificial neural network is a massively parallel, dynamic system of interconnected, interacting parts based on some aspects of the brain. Neural networks are considered to be intuitive because they learn by example rather than by following programmed rules. The ability to "learn" is one of the key aspects of neural networks. A neural network consists of several layers of neurons that are connected to each other. A *connection* is a unique information transport link from one sending to one receiving neuron. The structure of part of an NN is schematically shown in Figure 6.29. Any number of input, output, and "hidden layer" neurons can be used (only one hidden layer is shown). One of the challenges of this technology is to construct a net with sufficient complexity to learn accurately without imposing a burden of excessive computational time.

The neuron is the fundamental building block of a network. A set of inputs is applied to each. Each element of the input set is multiplied by a weight, indicated by the W in the figure, and the products are summed at the neuron. The symbol for the summation of weighted inputs is termed *INPUT* and must be calculated for each neuron in the network. In equation form this process for one neuron is

$$INPUT = \sum_i O_i W_i + B \tag{6.20}$$

where O_i are inputs to a neuron, i.e., outputs of the previous layer, W_i are weights, and B is the bias. After *INPUT* is calculated, an activation function, F, is applied to modify it, thereby producing the neuron's output as described shortly.

Artificial networks have been trained by a wide variety of methods (McClelland and Rumelhart 1988). Back-propagation is one systematic method for training multilayer neural networks. The weights of a net are initiated with small random numbers. The objective of training the network is to adjust the weights iteratively so that application of a set of inputs produces the desired set of outputs matching a training data set. Usually a network is trained with a data set that consists of many input–output pairs; these data are called a *training set*. Training the net using back-propagation requires the following steps:

1. Select a training pair from the training set and apply the input vector to the network input layer.
2. Calculate the output of the network, OUT_i.
3. Calculate the error, $ERROR_i$, the network output, and the desired output (the target vector from the training pair).
4. Adjust the weights of the network in a way that minimizes the error.
5. Repeat steps 1 through 4 for each vector in the training set until the error for the entire set is lower than the user specified, preset training tolerance

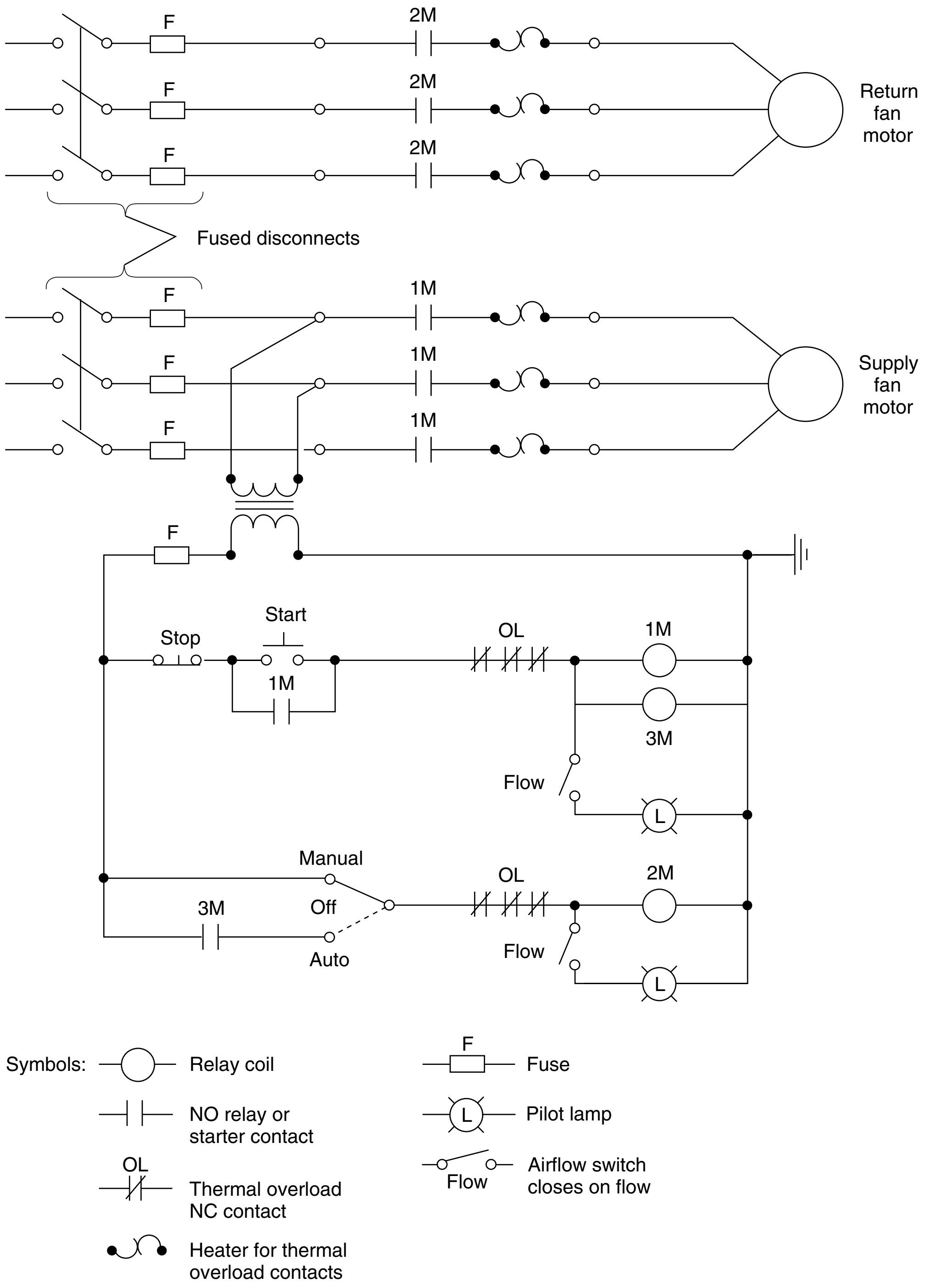

FIGURE 6.29 Ladder diagram for supply and return fan control. Hand-off auto switch permits manual or automatic control of the return fan.

Steps 1 and 2 are the "forward pass." The following expression describes the calculation process in which an activation function, *F*, is applied to the weighted sum of inputs, *INPUT*, as follows.

$$OUT = F(INPUT) = F\left(\sum_i O_i W_i + B\right), \tag{6.21}$$

where *F* is the activation function and *B* is the bias of each neuron.

The activation function used for this work was selected to be

$$F(INPUT) = \frac{1}{1 + \mathrm{e}^{-INPUT}}. \tag{6.22}$$

This is referred to as a *sigmoid function* and is shown in Figure 6.30. It has a value of 0.0 when *INPUT* is a large negative number and a value of 1.0 for large and positive *INPUT*, making a smooth transition between these limiting values. The bias, *B*, is the activation threshold for each neuron. The bias avoids the tendency of a sigmoid function to get "stuck" in the saturated, limiting value area.

Steps 3 and 4 comprise the "reverse pass" in which the delta rule is used as follows: for each neuron in the output layer, the previous weight $W(n)$ is adjusted to a new value $W(n+1)$ to reduce the error by the following rule:

$$W(n+1) = W(n) + (\eta\delta)OUT, \tag{6.23}$$

where $W(n)$ is the previous value of a weight, $W(n+1)$ is the weight after adjusting, η is the training rate coefficient. δ is calculated from

$$\delta = \left(\frac{\partial INPUT}{\partial OUT}\right)(TARGET - OUT) = OUT(1 - OUT)(TARGET - OUT), \tag{6.24}$$

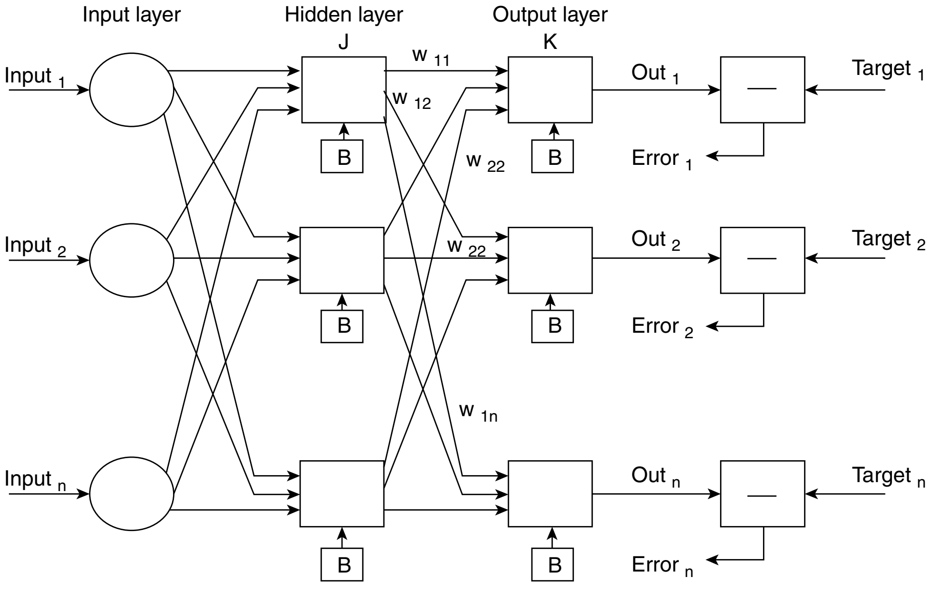

FIGURE 6.30 Schematic diagram of a neural network showing input layer, hidden layers, and output along with target training values. Hidden and output layers consist of connected neurons; the input layer does not contain neurons.

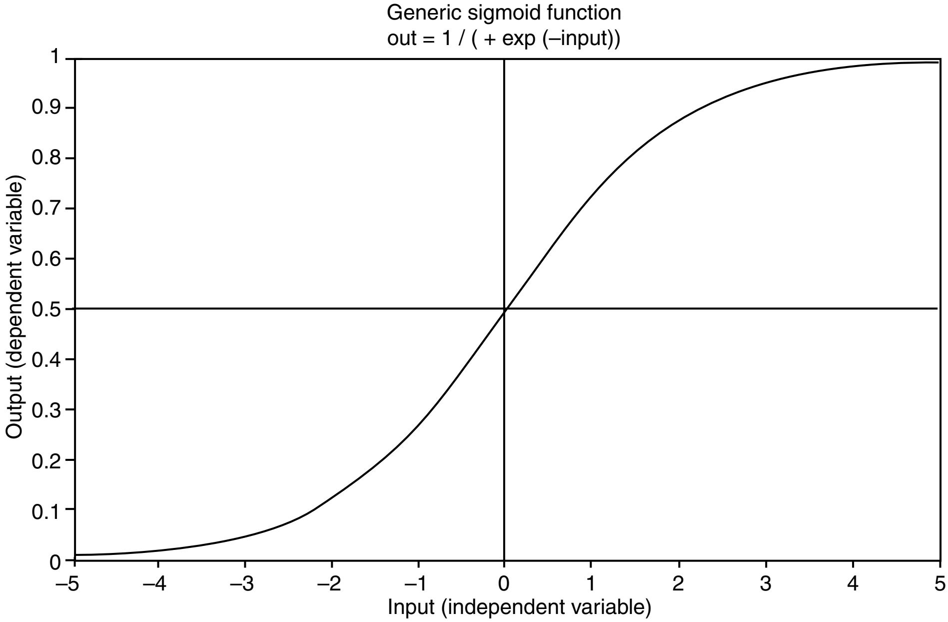

FIGURE 6.31 Sigmoid function used to process the weighted sum of network inputs.

in which the derivative has been calculated from Equation 6.21 and Equation 6.22, and *TARGET* (see Figure 6.29) is the training-set target value. This method of correcting weights bases the magnitude of the correction on the error itself.

Of course, hidden layers have no target vector; therefore, back-propagation trains these layers by propagating the output error back through the network layer by layer, adjusting weights at each layer. The delta rule adjustment δ is calculated from

$$\delta_j = OUT(1-OUT)\sum(\delta_{j+1}W_{j+1}) \tag{6.25}$$

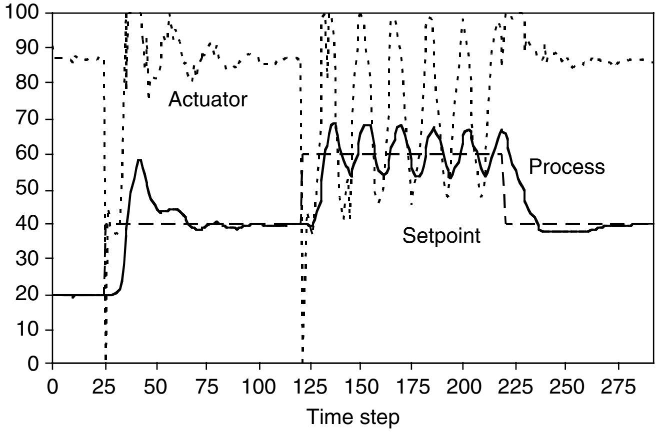

FIGURE 6.32 PID controller response to step changes in coil load. Proportional gain of 2.0. (From Curtiss, P. S., Kreider, J. F., and Brandemuehl, M. J., *ASHRAE Transactions*, 99 (1) 1993.)

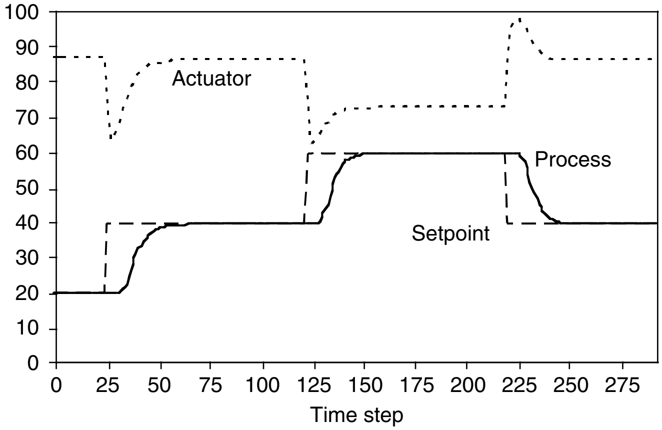

FIGURE 6.33 NN controller with learning rate of 1.0 and window of 15 time steps. (From Curtiss, P. S., Kreider, J. F., and Brandemuehl, M. J., *ASHRAE Transactions,* 99 (1) 1993.)

where δ_j and δ_{j+1} belong to the *j*th and $(j+1)$th hidden layers, respectively (being numbered with increasing values from left to right in Figure 6.29). This overall method of adjusting weights belongs to the general class of steepest descent algorithms. The weights and biases after training contain meaningful system information; before training, the initial, random biases and random weights have no physical meaning.

6.7.2 Commercial Building Adaptive Control Example

A proof of concept experiment in which neural networks (NNs) were used for both local and global control of a commercial building HVAC system was conducted in the JCEM laboratory in which full-scale, repeatable testing of multizone HVAC systems can be done. Data collected in the laboratory were used to train NNs for both the components and the full systems involved (Curtiss, Brandemuehl, and Kreider 1993; Curtiss, Kreider, and Brandemuehl 1993). Any neural network-based controller will be useful only if it can perform better than a conventional PID controller. Figure 6.31 and Figure 6.32 show typical results for the PID and NN control of a heating coil. The difficulty that the PID controller experienced is due to the highly nonlinear nature of the heating coil. A PID controller tuned at one level of load is unable to control acceptably at another, while the NN controller does not have this difficulty. With the NN controller, excellent control is demonstrated—minimal overshoot and quick response to the setpoint changes.

In an affiliated study, Curtiss, Brandemuehl, and Kreider (1993) showed that NNs offered a method for global control of HVAC systems as well. The goal of such controls could be to reduce energy consumption as much as possible, while meeting comfort conditions as a constraint. Energy savings of over 15% were achieved by the NN method vs. standard PID control (Figure 6.33).

6.8 Summary

This chapter has introduced the important features of properly designed control systems for HVAC applications. Sensors, actuators, and control methods have been described. Methods for determining control system characteristics, either analytically or empirically, have been discussed.

The following rules (adapted from ASHRAE 1987) should be followed to ensure that the control system is as energy efficient as possible. Neural networks offer one method for achieving energy efficient control.

1. Operate HVAC equipment only when the building is occupied or when heat is needed to prevent freezing.
2. Consider the efficacy of night setback vis à vis building mass. Massive buildings may not benefit from night setback due to the overcapacity needed for the morning pickup load.
3. Do not supply heating and cooling simultaneously. Do not supply humidification and dehumidification at the same time.
4. Reset heating and cooling air or water temperature to provide only the heating or cooling needed.
5. Use the most economical source of energy first, the most costly last.
6. Minimize the use of outdoor air during the deep heating and cooling seasons, subject to ventilation requirements.
7. Consider the use of "dead-band" or "zero-energy" thermostats.
8. Establish control settings for stable operation to avoid system wear and to achieve proper comfort.
9. Commission the control system and HVAC system for optimum efficiency based on actual building conditions and use.

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7

Energy-Efficient Lighting Technologies and Their Applications in the Commercial and Residential Sectors

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7.1 Introduction

Lighting is an important electrical end use in every sector and building type across the United States (U.S.). In 2003, approximately one-third of commercial and almost one-fifth of residential delivered (site) electricity consumption was attributable to lighting, or about one-quarter of all electricity delivered to these two sectors combined [6]. The commercial sector consumes the majority of the electricity used for lighting in the U.S. In 2001, the commercial sector consumed approximately 51% of total lighting electricity, the residential sector consumed 27%, the industrial sector consumed 14%, and outdoor stationary lighting was responsible for 8% [11].

There is great potential for saving electricity, reducing the emission of greenhouse gases associated with electricity production, and reducing consumer energy costs through the use of more efficient lighting technologies as well as advanced lighting design practices and control strategies. New, efficient technologies that enter the market in the future can further reduce energy use and increase financial savings.

In this chapter, we provide an overview of both conventional and newer, more efficient lighting technologies. The discussion includes:

- Design of energy-efficient lighting systems;
- Descriptions, applications, and efficacies of various lighting technologies (including lamps, ballasts, fixtures, and controls);
- Operation of energy-efficient lighting systems;
- Current lighting markets and trends;
- Lighting efficiency standards and incentive programs; and
- Cost-effectiveness of efficient lighting technologies.

7.2 Design of Energy-Efficient Lighting Systems

A lighting system is an integral part of a building's architectural design, and interacts with the shape of each room, its furnishings, and the level of natural light. Energy efficiency is an important component of lighting system design; however, lighting designers must also consider economics, productivity, aesthetics, and consumer preference. It is highly important not to compromise lighting *quality* in a new lighting design or energy-efficiency retrofit. To improve the lighting efficiency in a building, a lighting designer must understand the user's lighting needs and tastes, the most efficient technologies available to meet these needs, and the way in which individual lighting components function together as a system.

Efficient, high-quality lighting design includes:

- Attention to task and ambient lighting,
- Effective use of daylighting,
- Effective use of lighting controls, and
- Use of the most cost-effective and efficacious technologies.

Because people require less light in surrounding areas than they do where they perform visual tasks, it is usually both unnecessary and inefficient for an entire space to be lit at a level that is appropriate for visual tasks. For this reason, lighting designers practice task-ambient lighting design. For visual comfort and ease of visual transition between task and ambient spaces, the ambient lighting in a room should be at least one-third as bright as the lighting of the task areas. A common task-ambient lighting strategy is to design the overall lighting system to provide an appropriate ambient level of light and then add task lights (e.g., desk lamps) in areas where people are working.

Effective use of daylighting is also an important component of lighting system design. After decades of overdependence on artificial light, many lighting designers are returning to the use of sunlight to illuminate interior spaces. To make good use of natural light, however, requires more than the simple addition of multiple windows. Light pouring in through windows can create glare and cause other spaces to appear very dark by comparison; in addition, windows that are too large can allow too much heat loss or gain. The challenges to successful daylighting are to admit only as much light as needed, distribute it evenly, and avoid glare. The effective use of daylighting can be greatly enhanced by the overall architectural design of a building. For example, more sunlight is available to a building design that maximizes surface area (e.g., a building that is U-shaped or has an interior courtyard). In addition, skylights, wide windowsills, reflector systems, louvers, blinds, and other innovations can be used to bounce natural light farther into a building. The use of window glazes can limit heat transmission while permitting visible light to pass through a window or skylight.

Efficient lighting design depends on the careful selection of cost-effective and efficient lighting technologies. Lighting control systems are important components of efficient lighting systems. In order to complement other efficiency improvements, lighting designers can use lighting controls to reduce lighting when it is not needed. For example, lighting energy is saved when occupancy sensors turn off the lights after occupants leave a space or daylighting controls dim the fluorescent lamps as the level of natural light in a room increases. Dimming systems can also be used to maintain a constant light level as a system ages, which saves energy when lamps are new. To ensure the persistence of energy savings, lighting designers can install permanent lighting fixtures that are dedicated to efficient lamps. For example, an office retrofit substituting compact fluorescent lamps (CFLs) for screw-in incandescent lamps should utilize hard-wired CFL fixtures, which ensures that the more efficient CFLs will not be replaced with incandescent lamps at a later date.

Lighting design that promotes energy-efficient lighting technologies can also influence the design and energy use of a building's cooling system. Because efficient lighting systems produce less heat, the air conditioning systems installed in new buildings with efficient lighting can have lower capacities. Consequently, less money is spent on air conditioning systems as well as on cooling energy[1] The cost-effectiveness of efficient lighting systems is discussed in Section 7.7 below.

7.3 Lighting Technologies: Description, Efficacy, Applications

Lighting system components fall into four basic categories:

- Lamps,
- Ballasts,
- Fixtures, and
- Lighting controls.

In this section, we first discuss the properties of light sources and common lighting terms (see also Glossary). We then describe the most common and the efficacious lighting technologies within each category as well as where and how different technologies are used. In addition, we discuss some of the most promising design options for further efficiency improvements in lighting technologies.

7.3.1 Properties of Light Sources

Because the purpose of a lamp is to produce light, and not just radiated power, there is no direct measure of lamp efficiency. Instead, a lamp is rated in terms of its *efficacy*, which is the ratio of the amount of light emitted (lumens) to the power (watts) drawn by the lamp. For systems using a ballast, in this chapter we report *system efficacy*, which includes the watts drawn by the lamp and ballast. The unit used to express efficacy is lumens per watt (LPW). The theoretical limit of efficacy is 683 LPW and would be produced by an ideal light source emitting monochromatic radiation with a wavelength of 555 nm. The most efficient white light source in the laboratory provides 275–310 LPW. Of lamps presently in the market, the most efficient practical light source, the T5 fluorescent lamp with electronic ballast, produces about 100 LPW. High-pressure sodium (not a white light source) can produce as high as 130 LPW [9].

The efficacies of various light sources are depicted in Figure 7.1. Lamps also differ in terms of their cost, size, color, lifetime, optical controllability, dimmability, *lumen maintenance*, reliability, convenience in

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[1] More energy may be required to heat a building when lighting electricity consumption is reduced but, in many climate zones and building types, cooling savings offset this heating penalty and net cost savings are accrued.

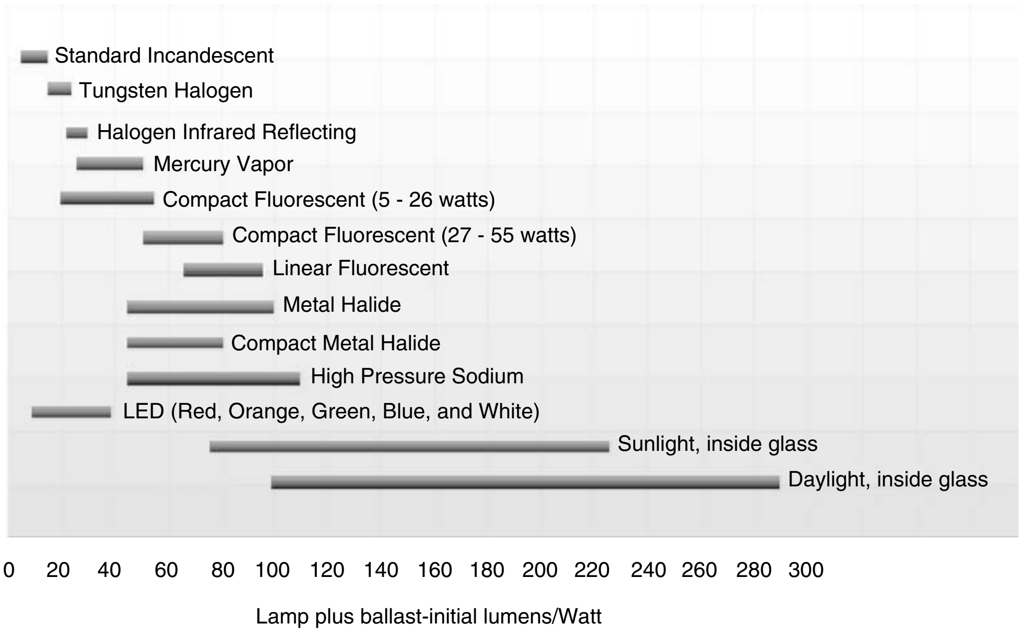

FIGURE 7.1 Efficacy comparison of light sources for general lighting. (From NBI 2003. *Advanced Lighting Guidelines, 2003*, New Buildings Institute, White Salmon, WA. With permission.)

use, maintenance requirements, disposal, environmental impacts (mercury, lead), and electromagnetic and other emissions (e.g., radio interference, ultraviolet (UV) light, and noise).

Over time, most lamps continue to draw the same amount of power but produce fewer lumens. The lumen maintenance of a lamp refers to the extent to which the lamp sustains its lumen output, and therefore efficacy, over time. Initial lumens are measured at the beginning of the lamp's life, while mean lumens are measured after a lamp has been used for a percentage of its rated life.

The color properties of a lamp are described by its color temperature and its color rendering index. *Color temperature*, expressed in degrees Kelvin (K), is a measure of the color appearance of the light of a lamp. The concept of color temperature is based on the fact that the emitted radiation spectrum of a blackbody radiator depends on temperature alone. The color temperature of a lamp is the temperature at which an ideal blackbody radiator would emit light that is closest in color to the light of the lamp. Lamps with low color temperatures (3000 K and below) emit warm white light that appears yellowish or reddish in color. Incandescent and warm-white fluorescent lamps have a low color temperature. Lamps with high color temperatures (3500 K and above) emit cool white light that appears bluish in color. Cool-white fluorescent lamps have a high color temperature.

The color rendering index (CRI) of a lamp is a measure of how surface colors appear when illuminated by the lamp compared with how they appear when illuminated by a reference source of the same color temperature. For color temperatures above 5000 K, the reference source is a standard daylight condition of the same color temperature; below 5000 K, the reference source is a blackbody radiator. The CRI of a lamp indicates the difference in the perceived color of objects viewed under the lamp and the reference source. There are 14 differently colored test samples, 8 of which are used in the calculation of the general CRI index. The CRI is measured on a scale that has a maximum value of 100 and is an average of the results for the eight colors observed. A CRI of 100 indicates that there is no difference in perceived color for any of the test objects; a lower value indicates that there are differences. Color rendering indexs of 70 and above are generally considered good, while CRI values of 20 and below are considered poor. Most incandescent lamps have CRI values equal to or approaching 100. Low-pressure sodium (LPS) lamps have the lowest CRI of any common lighting source; their light is essentially monochromatic.

The optical controllability of a lamp describes the extent to which a user can direct the light of the lamp to the area where it is desired. The optical controllability depends on the size of the light-emitting area, which determines the beam spread of the light emitted. In addition, controllability depends on the fixture in which the lamp is used. Incandescent lamps emit light from a small filament area: they are almost point sources of light, and their optical controllability is excellent. In contrast, fluorescent lamps emit light from their entire phosphored bulb wall area; their light is extremely diffuse, and their controllability is poor.

Because of the many different characteristics and the variety of applications, no one light source dominates the lighting market. The types of lamps that are commonly available include incandescent, fluorescent, and high-intensity discharge (HID). Induction lighting systems have come into use as well.

7.3.2 Lamps

An electric lamp is a device that converts electric energy into light. Following is a description of common lamp types with discussion on their efficacy and applications.

7.3.2.1 Incandescent Lamps

The *incandescent lamp* was invented independently by Thomas Edison in the United States and Joseph Swan in England in the late 1800s. An incandescent lamp produces light when electricity heats the lamp filament to the point of incandescence. In modern lamps the filament is made of tungsten. Because 90% or more of an incandescent lamp's emissions are in the infrared (thermal) rather than the visible range of the electromagnetic spectrum, incandescent lamps are less efficacious than other types of lamps.

The two primary types of standard incandescent lamps are general service and reflector lamps. General-service lamps (also known as A-lamps) are the pear-shaped, common household lamps. A reflector lamp has a reflective coating applied to part of the bulb, this reflective surface (reflector) is specifically contoured for control of the light distribution. Parabolic aluminized reflector (PAR) lamps have optically contoured reflectors. Reflector lamps, such as flood or spotlights, are generally used to illuminate outdoor areas or highlight indoor retail displays and artwork. They are also commonly used to improve the optical efficiency of downlights (recessed can fixtures). Downlights are used where controlling glare or hiding the light source is important. In spite of the fact that they are the least efficacious lamps on the market today, standard incandescent general service lamps are used for almost all residential lighting in the U.S. and are also common in the commercial sector. They have excellent CRI values and a warm color; they are easily dimmed, inexpensive, small, lightweight, and can be used with inexpensive fixtures; and, in a properly designed fixture, they permit excellent optical control. In addition, incandescent lamps make no annoying noises, provide no electro-magnetic interference and contain no toxic chemicals essentially. Incandescent lamps have relatively simple installation, maintenance, and disposal.

Tungsten–halogen and *tungsten–halogen infrared-reflecting (HIR) lamps* are more efficient than standard incandescents. Like standard incandescent lamps, tungsten-halogen lamps produce light when electricity heats the tungsten filament to the point of incandescence. In a standard incandescent lamp, tungsten evaporating from the filament deposits on the glass envelope. Generally, tungsten–halogen lamps use a quartz envelope rather than a glass envelope, which allows the lamp to operate at a much higher temperature. In place of the normal inert gas fill, the tungsten–halogen lamps use a small amount of halogen gas. The halogen gas in the lamp reacts with the tungsten that deposits on the quartz envelope to make a volatile tungsten–halide compound; because tungsten–halide vapor is not stable at the temperature of the filament, the vapor dissociates and deposits the tungsten back onto the filament. The cycle is then repeated. This cycle does not necessarily return the tungsten to the same portion of the filament from which it evaporated, but it does substantially reduce net evaporation of tungsten and thus prolong the life of the filament.

Halogen lamps produce bright white light and have color temperatures and CRI values that are similar to, or slightly higher than, those of standard incandescents. In addition, they have longer rated lives (2000 or more hours vs. 1000 h or less), can be much more compact, are slightly more efficacious, and have better lumen maintenance than standard incandescent lamps. Halogen general service lamps are available but still relatively rare; they offer longer life as well as slightly higher lumen output or lower wattage. Halogen reflector lamp technology has gained the market share for reflector lamps, because this technology meets the efficacy requirements of the Energy Policy Act of 1992, as discussed in Section 7.6. Halogen technology is also used in small reflector lamps operated on low-voltage transformers. These lamps, also known as dichroics, are used for accent lighting and sparkle in a variety of applications.

Even more efficacious than the standard tungsten–halogen lamp is the HIR lamp. Because approximately 90% of the energy radiated by incandescent lamps is in the form of heat (infrared radiation), their efficacy can be improved by reflecting the infrared portion of the spectrum back onto the lamp filament. Tungsten–halogen infrared-reflecting lamps use a selective, reflective, thin-film coating on the halogen-filled capsule or on the reflector surface. The coating transmits visible light, but reflects much of the infrared radiation back to the filament hence takes less electricity to heat it. The HIR technology is available in reflector lamps. In general, HIR lamps have a small market share due to their high cost, even though HIR lamps last about 50% longer than regular halogen lamps.

Torchieres, floor lamps that reflect light off the ceiling into the room, became popular in the mid-1990s, especially in the residential sector. The first torchieres were equipped with 300 or 500 W halogen lamps, but these are gradually being phased out. Their high wattages not only caused high energy use, but the lamp temperature was high enough to be a serious fire hazard. The high-wattage halogen lamps can reach almost 1000°F, hot enough to ignite a drape or other combustible material. Because of the resulting fires, some fire departments and college campuses have outlawed halogen torchieres. From an energy perspective, several states have implemented standards to limit the total wattage allowable in the fixture (typically no more than 190 W). As discussed in Section 7.6, similar national standards took effect in 2006. Incandescent torchieres presently dominate the market, typically using 150-W bulbs, but more efficient torchiere lamps equipped with various types of fluorescent lamps are available in the market place. A torchiere using a fluorescent lamp drawing 50–70 W costs more than a halogen or incandescent torchiere, but saves energy costs over its lifetime. (See Section 7.7).

7.3.2.2 Fluorescent Lamps

Fluorescent lamps came into general use in the 1950s. In a fluorescent lamp, gaseous mercury atoms within a phosphor-coated lamp tube are excited by an electric discharge. As the mercury atoms return to their ground state, ultraviolet radiation is emitted. This UV radiation excites the phosphor coating on the lamp tube and causes it to fluoresce, thus producing visible light.

Early fluorescent tubes, and current compact fluorescents lamps as well as some shorter fluorescent tubes, use “preheat start” with an automatic or manual starting switch. “Instant start” lamps were then developed, which uses a high voltage to strike the arc of the lamp. Electronic ballasts (see below) are available that can instant-start most types of fluorescent lamps. “Rapid start” circuits use low-voltage windings for preheating the electrodes and initiating the arc to start the lamps.

Fluorescent lamps are far more efficacious than incandescent lamps. The efficacy of a fluorescent lamp system depends upon the lamp length and diameter, the type of phosphor used to coat the lamp, the type of *ballast* used to drive the lamp, the number of lamps per ballast, the temperature of the lamp (which depends on the fixture and its environment), and a number of lesser factors.

The majority of lighting used in the commercial sector is fluorescent. Fluorescent lighting is also common in the industrial sector. The small amount of full-size fluorescent lighting in the residential sector is primarily found in kitchens, bathrooms, garages and workshops.

Full Size Fluorescent Lamps—The most common fluorescent lamps are tubular and 4 ft. (1.2 m) in length. The next most common length is 8 ft. (2.4 m). Fluorescent lamps are also available in 2-, 3-, 5-, and 6-ft. lengths. Four-feet lamps are also available in U-tube shapes that fit into fixtures with two-feet dimensions. Lamp tubes with a diameter of 1.5 in. (38 mm) are called T12s, tubes that are 1 in (26 mm) in diameter are called T8s, and those that are 5/8 in. (16 mm) are called T5s. (The 12, 8 and 5 refer to the number of eights of an inch in the diameter of the lamp tube.) Lamp tubes are available in other diameters as well. Each type of fluorescent lamp requires a specific ballast, depending on the wattage, length, and current (milliamps) of the lamp.

Fluorescent lamps have long lives and fairly good lumen maintenance. While the reduced wattage halophosphor (cool-white and warm-white) lamps have CRI values in the range of 50–60, rare-earth phosphor lamps have CRI values in the range of 70s and 80s. Fluorescent lamps have rated lifetimes of 12,000 h (8-ft. T12) to 20,000 h (4-ft. T12s and T8s used with rapid start ballasts) When 4-ft. T8s are used with instant start ballasts and frequently switched on and off, their lifetime is decreased to 15,000 h. High-performance (third generation) T8 lamps, also known as "super T8s," with 24,000–30,000 h rated lives and higher CRI values are now available. T5 lamps with better optical control and aesthetics are often used in high ceiling applications and indirect fixtures. T5 lamps are shorter in length than T12 and T8 lamps and require fixtures designed specially for their use. For example, the 28 W T5 lamp is 45.2 in. (1.14 m) in length.

T8 lamps can be operated on magnetic ballasts, but are most commonly used with high-frequency electronic ballasts. Operation with electronic ballasts increases the lamp efficacy by about 9% over operation with magnetic ballasts. T5 lamps operate exclusively with electronic ballasts. The maximum efficacy of a T5 lamp is slightly higher than that of a T8 lamp, and is achievable in ambient conditions about 10°C warmer than those optimal for T8 or T12 lamps. T8 and T5 high output lamps are also available for higher ceiling applications, but this application must be designed to prevent overheating the ballast. Eight-feet lamps have long been available in high-output (HO) and very-high-output (VHO) versions for use in higher ceiling applications.

The most common T12 lamps that meet the present EPAct 1992 lamp standards are reduced-wattage or "energy saver" lamps—for example, the 34-W four-feet lamp. These lamps became popular in the 1970s to retrofit full-wattage lamps (e.g. 40 W lamps). The reduced wattage lamp is similar to its full-wattage predecessor, with krypton added to the gas fill and a conductive coating to lower starting voltage. The lumen output is generally reduced proportionate to the wattage reduction. Previously common 40 W lamps with halophosphors do not meet the EPAct 1992 lamp standards; however, 40 W lamps are available with rare-earth phosphors and higher efficacy that do meet the standards and have a small part of the market share.

For more information about the EPAct 1992 fluorescent lamp standards, see Section 7.6, Lighting Efficiency Standards and Incentive Programs.

The specified or nominal wattage of a lamp refers to the power draw of the lamp alone. The ballast typically adds another 10%–20% to the power draw, thus reducing system efficacy. Of the full-size fluorescent lamps available today, *rare-earth phosphor lamps* are the most efficacious. In these lamps, rare-earth phosphor compounds are used to coat the inside of the fluorescent lamp tube. Rare earth phosphor lamps are also called tri-phosphor lamps because they are made with a mixture of three rare earth phosphors that produce visible light of the wavelengths to which the red, green, and blue retinal sensors of the human eye are most sensitive. These lamps have improved color rendition as well as efficacy. Fluorescent T8 and T5 lamps and those with smaller diameters use rare earth phosphors almost exclusively.

The most common efficient fluorescent lamp-ballast systems available today are T8 lamps operating with electronic ballasts. While two T12 34 W halophosphor lamps with an energy saving magnetic ballast have a mean efficacy (with mean lumens) of 54 LPW, two standard 32-W T8 lamps with standard instant-start ballast have a mean efficacy of 75 LPW. *High-performance* T8 systems have evolved over the last few years through a succession of incremental improvements in lamp barrier coatings, phosphors, cathodes, and gas fills, and in ballast circuitry and components.[2] The technical improvements provide higher initial light output, better lumen maintenance, longer life and improved ballast efficiency. High-performance instant start T8 lamp/ballast systems have the highest mean efficacy of any "white" light source at 90 LPW (two-lamp system). The same T8 lamp system with a programmed start ballast has a mean efficacy of 82 LPW [2]. Other T8 lamps offer efficacies above the standard T8 systems, such as four-foot T8 lamps in 25, 28 and 30 W versions that operate on the same electronic ballasts as do 32 W T8 lamps, but these lamps have some operating constraints. There are also T8 lamps with higher light output or longer lamp life than standard T8s, although they don't offer the combined benefits of the high-performance T8 systems.

The Consortium for Energy Efficiency (CEE), a national, nonprofit organization, developed a specification to consistently define high-performance T8 lamps and ballasts. This specification, shown in Table 7.1, was developed for voluntary usage by utilities and energy-efficiency organizations promoting high-performance commercial lighting systems. A listing of qualifying products can be found on the CEE website at www.cee1.org.

Note: The specification and qualifying products list are updated and revised periodically. Please refer to the CEE website for the most current information.

Presently, the installed cost of a high-performance T8 system is more than the of a T12 or a standard T8 system; however, that cost differential is shrinking. The increased efficacy and longer life of the high-performance systems make them the best economic choice for most applications. (See Section 7.7).

In spite of their much greater efficiency, fluorescent lamps have several disadvantages when compared with incandescent lamps. Standard and compact fluorescent lamps can be dimmed, but require special dimming ballasts that cost more than the dimming controls used for incandescent lamps. Standard fluorescent lamps are larger than incandescent lamps of equivalent output and are harder to control optically. Fluorescent lamps also emit more UV light than incandescent lamps. Ultraviolet light can cause colors to fade, and fabrics to age, and therefore has to be blocked near sensitive materials like museum displays. Electronic ballasts may interfere with security equipment, such as that used in libraries and with specialized hospital devices.

Fluorescent lamps contain trace amounts of mercury, a toxic metal, and large users are required to either recycle them or dispose of them as hazardous waste. However, mercury is also emitted through the electricity production process, and the net total emission of mercury including the power plant emissions is actually lower for fluorescent lamps than for the incandescent lamps that they replace. Lamp manufacturers have begun to produce fluorescent lamps with lower mercury content that meet U.S. Environmental Protection Agency requirements and allow disposal of small quantities of lamps. Regulations vary by state; for more information, see www.lamprecycle.org or http://www.almr.org/.

Circular Fluorescent Lamps—Circular-shaped fluorescent lamps in 20–40-W sizes have been available for many years, but have had a fairly small market. Essentially, a circular lamp is a standard fluorescent lamp tube (as described earlier) that has been bent into a circle. Although they have a more compact geometry than a straight tube, circular lamps are still moderately large (16.5–41 cm in diameter). Circular lamps are available in several sizes with magnetic or electronic ballasts.

Compact Fluorescent Lamps—Compact fluorescent lamps, which are substantially smaller than standard fluorescent lamps, were introduced to the U.S. market in the early 1980s. In a CFL, the lamp tube is smaller

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[2] The three major U.S. lamp manufacturers have each developed high-performance T8 lamps: GE High Lumen ECO, Philips Advantage Alto, and Sylvania Xtreme XPS EcoLogic. ("ECO" and "ALTO" identify the lamps as low mercury.) Five manufacturers offer high-performance T8 ballasts: Advance Optanium, GE Ultramax, Howard Industries HEX, Sylvania QHE, and Universal Ultim8.

TABLE 7.1 CEE T8 High-Performance Specification

Performance Characteristics for Lamps				
Mean System Efficacy	≥ 90 MLPW for Instant Start Ballasts ≥ 88 MLPW for Programmed Rapid Start Ballasts			
Color Rendering Index (CRI)	≥ 81			
Minimum Initial Lamp Lumens	≥ 3100 Lumens			
Lamp Life	≥ 24,000 hrs at three hours per start.			
Lumen Maintenance –or – **Minimum Mean Lumens**	≥ 94% –or– ≥ 2900 Mean Lumens			
Performance Characteristics for Ballasts				
Ballast Efficacy Factor (BEF) BEF = [BF × 100] / Ballast Input Watts **Based on:** (1) Type of ballast (2) No. of lamps driven by ballast (3) Ballast Factor	**Instant-Start Ballast (BEF)**			
	Lamps	Low BF ≤ 0.85	Norm 0.85 < BF ≤ 1.0	High BF ≥ 1.01
	1	≥ 3.08	≥ 3.11	n/a
	2	≥ 1.60	≥ 1.58	≥ 1.55
	3	≥ 1.04	≥ 1.05	≥ 1.04
	4	≥ 0.79	≥ 0.80	≥ 0.77
	Programmed Rapid-Start Ballast (BEF)			
	1	≥ 2.84	≥ 2.84	n/a
	2	≥ 1.48	≥ 1.47	n/a
	3	≥ 0.97	≥ 1.00	n/a
	4	≥ 0.76	≥ 0.75	n/a
Ballast Frequency	20 to 33 kHz or ≥ 40 kHz			
Power Factor	≥ 0.90			
Total Harmonic Distortion	≤ 20%			

Voluntary guidelines for use in energy-efficiency programs. For terms and usage, please see the CEE website (ww.w.cee1.org). MLPW = mean lumens per watt.

in diameter and is bent into two to six sections or into a spiral shape. The compact size of the spiral CFLs allow them to substitute for incandescent lamps in many fixtures. Compact fluorescent lamps have much higher power densities per phosphor area than standard fluorescents, and their design was therefore dependent on the development of rare-earth phosphors, which could hold up much better than standard phosphors at high-power loadings. Compact fluorescent lamps (except for very low-wattage CFLs) are much more efficacious than the incandescent lamps they replace, typically drawing one-third to one-quarter of the wattage for similar light output. They are, however, half as efficacious as high-performance T8 systems, hence they are more often cost-effective for applications or retrofits where a smaller light source is needed. Compact fluorescent lamps are also rated to last 6000–10,000 h, with some newer products having even longer rated lifetimes.

Compact fluorescent lamps are available as both screw-in replacements for incandescent lamps and as pin-base lamps for hard-wired fixtures. Common CFLs range from 11 to 26 W, and both higher and lower wattage lamps are available. They may be operated with separate ballasts or purchased as integral lamp/ballast units; integral units with electronic ballasts are the most commonly sold. The electronic ballast provides higher efficacy, eliminates the starting flicker and has a lighter weight. Compact fluorescent lamps have a much higher retail cost than the incandescent lamps they replace, hence consumers have been reluctant to purchase them without discounts or incentives; their prices have decreased with their increasing popularity. Particularly for the residential sector, CFLs have been somewhat limited for use in fixtures because their size and shape relative to incandescent lamps. Manufacturers have developed lamps with smaller, more compatible shapes, as well as adapters for some fixtures. Early CFL users in the residential sector encountered some starting problems at low temperatures for outdoor use and overheating in enclosed fixtures. Compact fluorescent lamps that start at low outdoor temperatures are now available. Standard CFLs may not be used in dimming circuits because of fire hazard, but dimmable CFLs became available during the late 1990s. Compact fluorescent lamps reflector lamps are also available. In the commercial sector, dedicated fixtures with built-in ballasts that accept only pin-based CFLs are often used in downlights, to ensure that screw-in incandescents do not replace the CFLs.

7.3.2.3 Induction Lamps

An induction lamp is a fluorescent lamp where the electric discharge is induced by a magnetic field, rather than an electric field as in a fluorescent lamp, and therefore does not have any electrodes. Induction lamps produce light by exciting the same phosphors found in conventional fluorescent lamps. The radio frequency (RF) power supply sends an electric current to an induction coil, generating an electromagnetic field. This field excites the mercury in the gas fill, causing the mercury to emit UV energy. The UV energy strikes and excites the phosphor coating on the inside of the glass bulb, producing light. Electrodeless lamps have efficacies similar to those of CFLs or HID lamps of comparable light output. Electrodeless lamps use rare-earth phosphors, giving them color properties similar to those of higher-end fluorescent lamps. Because the lamp has no electrodes that usually cause lamp failure, the life of this system is limited by the induction coil. Induction lamps are rated at 100,000 h of life. Because of this long life, and the good color rendition, induction technology is coming into use for areas where maintenance to change the lamp is expensive, such as high ceilings in commercial and industrial buildings, atria, tunnels, roadway sign lighting, etc.

Induction lamps are electronic devices, and like all electronic devices they may generate electromagnetic interference (EMI) if unwanted electromagnetic signals, which can travel through wiring or radiate through the air, interfere with desirable signals from other devices. Shielding of the system to protect people and equipment from these emissions is important. Manufacturers must comply with national regulations on EMI to sell products in any country.

7.3.2.4 High-Intensity Discharge Lamps

High-intensity discharge (HID) lamps produce light by discharging an electrical arc through a mixture of gases. In contrast to fluorescent lamps, HID lamps use a compact arc tube in which both temperature and pressure are very high. Compared to a fluorescent lamp, the arc tube in an HID lamp is small enough to permit compact reflector designs with good light control. There are presently three common types of HID lamps available: mercury vapor (MV), metal halide (MH), and high-pressure sodium (HPS). Additionally, low pressure sodium (LPS) lamps, while not technically HID lamps, are used in some of the same applications as HPS lamps.

Because of their higher light output levels, HID lamps are most often used for exterior applications such as street and roadway lighting, outdoor area pedestrian and parking lot lighting, commercial, industrial, and residential floodlighting and security lighting, and sports lighting. They are also used in large, high-ceilinged, interior spaces such as industrial facilities and warehouses, where good color rendering is not typically a priority. Occasionally, HID lamps are used for indirect lighting in commercial offices, retail stores, and lobbies. Interior residential applications are rare because of high cost, high light level, and the fact that HID lamps take several minutes to warm up to full light output. If they are turned off or there is a momentary power outage, the lamps must cool down before they restrike. Some HID lamps are now available with dual arc tubes or parallel filaments. Dual arc tubes eliminate the restrike problem and a parallel filament gives instantaneous light output both initially and on restrike, but at a cost of a high initial power draw and higher lamp cost.

The *mercury vapor lamp* was the first HID lamp developed. Including ballast losses, the efficacies of MV lamps range from approximately 25–50 LPW. Uncoated lamps have a bluish tint and very poor color rendering (CRI $\sim$ 15). Phosphor-coated lamps emit more red, but are still bluish, and have a CRI of about 50. Because of their poor color rendition, these lamps are used only where good color is not a priority. MV lamps generally have rated lifetimes greater than 24,000 h. Both MH and HPS HID lamps have higher efficacies than MV lamps and have consequently replaced them in most markets. MV lamps and ballasts are cheaper than the other HID sources and are still often sold as residential security lights. They also persist in some legacy street-lighting applications, landscape lighting, and in some other older systems.

Including ballast losses, *metal halide lamps* range in efficacy from 45 to 100 LPW. They produce a white light and have CRI values ranging from 65 to almost 90. Lamp lifetimes generally range from only 5000 to 20,000 h, depending on the type of MH lamp. Lower-wattage metal halides (particularly the 50, 70 and 100 W) are now available with CRI values of about 65–75 and color temperatures of 2900–4200 K. Reasonably good lumen maintenance, longer life, reduced maintenance costs, and the fact that they blend more naturally with fluorescent sources have made MH lamps a very good replacement in the commercial sector for 300 and 500 W PAR lamps. New fixtures utilizing these lamps, particularly 1-ft. by 1-ft. recessed lensed troffers (downlights), are becoming common in lobbies, shopping malls, and retail stores. Improvements in color stability have made MH systems cost-effective substitutions for high-wattage incandescent lighting in commercial applications.

Metal halide technology is also becoming increasing popular for outdoor lighting, especially in areas where color rendering is important, and because of people’s preference for “white light.” Pulse-start technology is improving MH lamp performance in almost every aspect. In MH pulse start lamps, a high-voltage pulse (typically 3 kV minimum) applied directly across the main electrodes initiates the arc. Ignitors are used to provide these starting pulses. The average lifetime of pulse-start MH lamps now approaches that of HPS and MV lamps. With the higher efficacy this technology provides, approaching that of HPS lamps, pulse-start MH lamps now compete with HPS lamps in many outdoor applications. Ceramic arc tube MH lamps, with CRI values as high as 90 and better color consistency, now compete with incandescent sources. MH lamps may fail “nonpassively,” hence users should always follow the manufacturers’ recommended practices for safe operation of the lamps.

At low light levels, such as those found in many outdoor areas at night, the eye’s peripheral vision becomes more sensitive to light that is bluish. Although MH lamps are less efficacious than HPS lamps at high, or “photopic” light levels found during daylight hours, they can actually provide higher visual quality and therefore allow lower light levels, making them more efficacious, at least for peripheral vision, than HPS lamps at low or “scotopic” levels. This has led to increased interest in their use for street lighting.

Including ballast losses, *high-pressure sodium lamps* have efficacies ranging from 45 LPW for the smallest lamps to 110 LPW for the largest lamps. Standard HPS lamps emit a yellow–orange light and have poor color rendition in the 20 s; high color rendering versions can have CRI values up to 70 and higher. Like MV lamps, HPS lamps are only used where good color is not a priority. HPS lamps have come to dominate street and roadway lighting because of their high efficacy and long life. The rated lifetimes of HPS lamps rival those of MV lamps and typically exceed 24,000 h.

For more information on the HID lamp market, see Section 7.5.

7.3.2.5 Low-Pressure Sodium Lamps

Low-pressure sodium (LPS) lamps are discharge lamps that operate at lower arc tube loading pressure than do HID lamps. Low-pressure sodium lamps are monochromatic in the yellow spectral band and have CRI values of 44. They have been used for street and tunnel lighting, especially in cities near astronomical observatories, because the LPS color spectrum can easily be filtered out so as not to interfere with telescopes. (In more recent efforts to limit "sky glow" as well as glare from outdoor lighting, the emphasis has shifted from lamp types to luminaire light control, with various styles of "cutoff" luminaires directing light downward and not upward, or using shielding to the same effect. For street lighting, calculations suggest that the match of the luminaire light distribution to the street, rather than the cutoff classification, is the most critical factor in limiting sky glow.) The LPS lamp has limitations for many applications where color rendering is important for safety and identification.

7.3.2.6 Light Emitting Diodes

Light emitting diodes (LEDs) are semiconductor diodes that emit light when current flows through them. They are available as narrowband light sources in "colors" ranging from the infrared to the near UV, and, with the addition of a phosphor coat, as a white light source with color temperatures ranging from 3200 to 12,000°K and CRI values ranging from 60 to over 90. Rated efficacies range up to 30 LPW for white LEDs, which is superior to that of incandescent lamps.

The present major disadvantages of LEDs relative to other light sources are their low maximum wattage per unit (presently 3–10 W) and their high unit cost. The present effective cost per watt (retail) is on the order of $3W. The cost of incandescent lamps is not strongly dependent on lamp wattage, which means that large incandescent lamps are 1000 times less expensive per watt than LEDs, but small ones are more comparable in price.

Light emitting diodes have other advantages over small incandescent lamps that are leading to their increasing dominance for battery operated lighting. Their usable life ranges from 6000 to 50,000 h (at 70% lumen maintenance). Small standard flashlight bulbs have thin filaments and can only manage 8–10 LPW and 15–30 h of lamp life. Light emitting diodes are durable, require less expensive optics for good beam control, and are available with high color temperatures, which lead to higher perceived brightness and better visibility in low light conditions. The power supplies used in the more expensive lights significantly increase the fraction of battery power available to provide useful amounts of light. LED bike lights and flashlights have battery lives that are a factor of 10 greater than those of comparable standard incandescent lights, and a factor of 3–5 greater than those of halogen lamps. The use of a flashing mode can increase this advantage even further.

Light emitting diodes are also displacing incandescent lamps in traffic signal lights and dynamic sign and color displays. Light emitting diodes have the advantage over incandescent lamps in these applications because filtering incandescent lamps to produce colors reduces their efficacy to the 2–3 LPW range, while switching on and off reduces their life. Light emitting diodes are also replacing incandescent and fluorescent light sources in exit signs. As discussed Section 7.6, EPAct 2005 contains standards for traffic and pedestrian signals that require LED technology, and for exit signs that require LED technology or technology with similar efficacies.

Manufacturers have announced that 60 LPW white LEDs will be available in the near future. This is comparable to the efficacy of small fluorescent lamps, and the industry target of 150 LPW by 2012 would make LEDs more efficacious than all but monochromatic LPS lamps. Research continues on organic LEDs (OLEDs), which are cheaper, but less efficacious than standard LEDs, and on manufacturing techniques to reduce the cost per unit of standard LEDs while increasing their wattage. The lack of toxic mercury in LEDs could make them preferable to small fluorescent lamps in a few years time, even if they are a bit more expensive, and their efficacy is no higher.

7.3.3 Ballasts

Because fluorescent and HID lamps (both discharge lamps) have a low resistance to the flow of electric current once the discharge arc is struck, they require a device to limit current flow. A lamp ballast is an electrical device used to control the current provided to the lamp. In most discharge lamps, a ballast also provides the high voltage necessary to start the lamp. Older preheat fluorescent lamps require a separate starter, but these lamps are becoming increasingly uncommon. In many HID ballasts, the ignitor used for starting the lamp is a replaceable module.

The most common types of fluorescent ballasts are magnetic core-coil and electronic high-frequency ballasts. A *magnetic core-coil ballast* uses a transformer with a magnetic core coiled in copper or aluminum wire to control the current provided to a lamp. Magnetic ballasts operate at an input frequency of 60 Hz and operate lamps at the same 60 Hz. An *electronic high-frequency ballast* uses electronic circuitry rather than magnetic components to control current. Electronic ballasts use standard 60 Hz power but operate lamps at a much higher frequency (20,000–60,000 Hz). Both magnetic and electronic ballasts are available for most fluorescent lamp types.

The *cathode cut-out (hybrid) ballast* is a modified fluorescent magnetic ballast. It uses an electronic circuit to remove the filament power after the discharge has been initiated for rapid-start lamps. Cathode cutout ballasts use approximately 5%–10% less energy than energy-efficient magnetic ballasts.

Of the ballasts that are presently available for fluorescent lamps, the most efficient option is the electronic ballast. Because an electronic ballast is more efficient than a standard core-coil magnetic ballast in transforming the input power to lamp requirements, and because fluorescent lamps are more efficient when operated at frequencies of 20,000 Hz or more, a lamp/ballast system using an electronic rather than magnetic ballast is more efficacious.

In addition, electronic ballasts eliminate flicker, weigh less than magnetic ballasts, and operate more quietly. Since electronic ballasts are packaged in cans that are the same size as magnetic ballasts, they can be placed in fixtures designed to be used with magnetic ballasts. Fluorescent electronic ballasts are available for standard commercial-sector applications. They have become increasingly popular, particularly in new luminaires as well as in energy-efficiency retrofits (see Section 7.5).

There are three basic starting modes for electronic ballasts. Rapid start ballasts apply continuous low filament voltage to preheat the cathode and use a higher starting voltage to strike the arc to start the lamp. Instant start ballasts apply high voltage across the lamp without preheating the cathode. This allows lower system wattage, but the instant starting shortens lamp life. Programmed start ballasts, a type of rapid start ballast developed most recently, apply cathode heat prior to starting the lamp and then lower or cease it once the lamp has started. Programmed start ballasts are recommended for use with occupancy sensors and frequently switched applications. For all other applications, instant-start ballasts are the more efficient choice. Advances in dimming fluorescent ballasts allow further energy savings through automatic controls.

Ballast factor indicates the light output of a lamp when operated with a specific ballast relative to the light output of the same lamp when operated with a reference ballast. Electronic ballasts are available with high and low ballast factors for higher or lower light levels where needed for specific applications.

The most commonly-used ballasts for HID lamps are magnetic, and a number of different types are available. The various types differ primarily in how well they tolerate voltage swings and, in the case of HPS lamps, the increased voltage required to operate the lamp as it ages. Electronic ballasts are also available, although the energy savings are less than for fluorescent systems. As with fluorescent systems, HID electronic ballasts provide flicker-free lighting and regulate lamp power, which increases lamp life, maintains constant color, and allows for precise starting, warm-up, and operation. Newer electronic HID ballasts improve system efficiency, are smaller in size and are becoming available in a wider range of wattages.

7.3.4 Lighting Fixtures

A lighting fixture is a housing for securing lamp(s) and ballast(s) and for controlling light distribution to a specific area. The function of the fixture is to distribute light to the desired area without causing glare or discomfort. The distribution of light is determined by the geometric design of the fixture as well as the material of which the reflector and/or lens is made. The more efficient a fixture is, the more is the light it emits from the lamp(s) within it. Although the term *luminaire* is sometimes used interchangeably with *fixture*, *luminaire* refers to a complete lighting system including a fixture, lamp(s) and ballast(/s).

Types of fluorescent lighting fixtures that are commonly used in the nonresidential sectors include recessed troffers, pendant-mounted indirect fixtures and indirect/direct fixtures, and surface-mounted fixtures such as wraparound, strip, and industrial fixtures.

Until recently, most offices have been equipped with *recessed lensed troffers*, which are direct (light emitted downward) fixtures and emphasize horizontal surfaces. Many forms of optical control are possible with recessed luminaires. In the past, prismatic lenses were the preferred optical control because they offer high luminaire efficiency and uniform illuminance in the work space. More recently, *parabolic louvered fixtures* have become common in office spaces. These fixtures have reflectors in the form of louvers, often aluminized, with parabolic geometry that directs light downward.

Offices with electronic equipment have become the norm, and until fairly recently there was a trend away from the traditional direct lighting fixtures designed for typing and other horizontal tasks because they tend to cause reflections on video display terminal (VDT) screens. No lighting system reduces glare entirely, but some fixtures and/or components can reduce the amount of glare significantly. Because the glossy, vertical VDT screen can potentially reflect bright spots on the ceiling, and because VDT work is usually done with the head up, existing fixtures are sometimes replaced with indirect or direct/indirect fixtures, which produce light that is considered more comfortable visually. Most indirect lighting systems are suspended from the ceiling. They direct light toward the ceiling where the light is then reflected downward to provide a calm, diffuse light. Some people describe the indirect lighting as similar to the light on an overcast day, with no shadows or highlights. Generally, indirect lighting does not cause bright reflections on VDT screens. A *direct/indirect fixture* is suspended from the ceiling and provides direct light as well as indirect. These fixtures combine the high efficiency of direct lighting systems with the uniformity of light and lack of glare produced by indirect lighting systems. New, flat-panel-liquid crystal display monitors are much less sensitive to reflections than the older cathode-ray tube VDTs, and this may affect the types of fixtures used in offices in the future.

A *wraparound fixture* has a prismatic lens that wraps around the bottom and sides of the lamp, and is always surface-mounted rather than recessed. Wraparound fixtures are less expensive than other commercial fixtures and are typically used in areas where lighting control and distribution are not a priority. *Strip and industrial fixtures* are even less expensive and are typically used in places where light distribution is less important, such as large open areas (grocery stores, for example) and hallways. These are open fixtures in which the lamp is not hidden from view.

The most common incandescent fixture in the nonresidential sector is the *downlight*, also known as a recessed can fixture. Downlights are also becoming increasingly popular for residential lighting. Fixtures designed for CFLs are available to replace incandescent downlight fixtures in areas where lighting control is less critical.

Interior HID luminaires include high bay and low bay fixtures (aisle lighters, parking garage, etc.), downlights, and accent lighting. Exterior HID luminaires include street and roadway fixtures (cobrahead, post-top, architectural), floods of all sizes and types (from sports to landscape), wall mounted, and security fixtures.

Luminaire Efficacy Rating is a single metric that expresses *luminaire efficacy*, the luminaire's light output divided by the input power. The formula is:

$$\text{LER} = \frac{\text{Luminaire efficiency (EFF)} \times \text{Total rated lamp lumens (TLL)} \times \text{Ballast factor (BF)}}{\text{Luminaire Watts input}}$$

Note that the effects of all components of the luminaire system (lamp, ballast and fixture) are included in the LER. The National Electrical Manufacturers Association (NEMA) Standards Publication No. LE5, “Procedure for Determining Luminaire Efficacy Ratings for Fluorescent Luminaires”, specifies the major fluorescent luminaire categories covered and the standard industry test procedures [14]. NEMA Publications LE5A and LE5B provide the specifications for commercial downlight luminaires [13] and HID industrial luminaires [12].

7.3.5 Lighting Controls

Lighting controls include a wide range of technologies that electronically and/or mechanically control the use of lights in a building. Control systems range from simple light switches and mechanical timeclocks to sophisticated building energy management systems that control the lighting in a building as well as the heating, ventilation, and air conditioning systems. Lighting control systems include programmable timers, occupancy sensors, photosensors, dimmers, switchable or dimmable ballasts, and communications and control systems. In the commercial sector, controls are used to save energy, curtail demand, or tailor the lighting environment to changes in lighting requirements. Both occupancy sensing and scheduling save energy by turning lights off or to a lower level when no one is present. Occupancy sensors, which sense people’s presence in the room by means of infrared or ultrasound signals that detect movement and turn lights off a short time after people leave the space, can save from 20 to 40% of lighting energy in the spaces they control. When implemented together with scheduling, where the lights are automatically turned off during known periods of nonoccupancy (with override capability for occupants), savings can be on the order of 50%. Daylighting controls dim or switch lights when there is sufficient daylight, and can save 30%–40% of the energy use for lighting along the building perimeter during the day. Demand curtailment can be performed during certain periods by a building energy management system by dimming or switching lights in response to high peak demand costs, or emergency conditions where there is a risk of power outages. Dimmable systems can be set to turn on at different levels in response to changes in occupancy or work demands. Transitional areas from outdoors to indoors (such as tunnel entrances and lobbies) can use dimming or switching systems to provide high light levels during bright day time conditions and lower levels at night. Older control systems may maintain light levels by increasing power to lamps as they age and lose their lumen maintenance and efficacy, but this is no longer considered economic and is discouraged.

Development of more accurate and reliable sensors, better communication between systems, and better integration of systems continues to increase the utility of control systems and the resulting energy savings. An integrated workstation sensor allows users to control not just lighting, but heating and cooling (space temperature), and other electrical equipment (such as plug loads) for individual workstations or spaces. Communication to a building energy management system allows the main system to set up and change defaults, over-ride individual settings in case of emergency, and monitor equipment status. Improvements in the spectral sensitivity of the photosensors, and improvements in the dimming algorithms, should lead to higher user satisfaction with daylighting systems, and consequently to larger energy savings. Users sometimes deliberately disable poorly functioning control equipment. Improvements in occupancy sensing, and scheduling algorithms, should help produce systems which are more likely to remain functioning, and thus actually save energy.

In the residential sector, the control of exterior lighting through photocells, motion sensors and time clocks is fairly common. Simple motion sensors turn outdoor lights on as occupants approach the home and turn them off a few minutes after they leave the area and also discourage burglars; photocells prevent daytime operation. These sensors sometimes experience false triggering from pets. Automatic controls for residential interior lighting are less common but have come into use. For example, scene controllers let residents set the levels of multiple lamps with a single command. Computer-controlled relays allow residents to use the internet to switch exterior lighting on when they are about to arrive home.

7.4 Efficient Lighting Operation

In addition to high quality design and the use of efficient lighting technologies, commissioning and maintenance of lighting systems play important roles in maximizing energy savings.[3] The commissioning process is necessary because lighting systems (particularly lighting controls) often do not perform exactly as they were designed to perform. Although often ignored, maintenance is essential for maximizing the efficient performance of lighting fixtures.

The presence of dirt on a luminaire can significantly reduce its light output. In a very clean environment (e.g., high-quality offices, clean rooms, laboratories), luminaire dirt is estimated to reduce light output over a period of 3 years by 10%–20%, depending upon the type of luminaire used. In a moderately dirty environment (e.g., mill offices, paper processing, light machining), dirt on luminaires can reduce light output by as much as 45% in 3 years. In a very dirty environment, light output can be reduced by 50% in less than 2 years. Dirt on the surfaces in a room can also reduce the available light by limiting the ability of surfaces to inter-reflect from one to another. Consequently, cleaning not only makes the lighting system and room look better, but also increases the efficiency of the lighting system.

Group relamping (replacing all lamps in an area or building simultaneously rather than as each lamp burns out) is another strategy for maintaining high-efficiency fluorescent and HID lighting systems and often saves time and money as well.[4] As mentioned above, most lamps become less efficacious and produce fewer lumens as they age. Therefore, if a lighting system is designed to maintain a minimum light level over many years, it must be designed to produce more than the minimum light level when first installed. Group relamping is usually done when the lamps have operated for about 75% of their rated lifetimes [16]. Even though the lamps are retired before the end of their useful lives, early relamping can greatly reduce the amount of initial over lighting that is necessary in the design and results in a more efficient lighting system. When compared with the high labor cost of replacing one lamp at a time, group relamping can often result in substantial labor cost savings. In addition, while replacing lamps, a maintenance crew has a convenient opportunity to clean lamp lenses and reflectors.

7.5 Current Lighting Markets and Trends

As a whole, the U.S. lamp industry is highly concentrated—almost all of the market is shared among a few firms. Lighting manufacturers are typically multinational corporations serving markets around the world. The U.S. ballast companies started out primarily as separate firms from the lamp companies, but in recent years each of the major lamp manufacturers have either purchased or become aligned with a major ballast company U.S. fixture manufacturers have seen a series of acquisitions over the past few decades and many firms are now subsidiaries of larger firms. Five or so fixture manufacturers account for more than one-half of the market share. In contrast to the concentrated markets for lamps, ballasts, and fixtures, there are many firms involved in the lighting controls market. The technologies in this group are highly varied; for example, some firms manufacture very simple timers while others manufacture highly complex control systems for whole buildings.

In this section we present details on market trends for HID lamps and fluorescent lamp ballasts. Details on market trends for most lamp types are difficult to track since the Census Bureau discontinued its Current Industrial Report on electric lamps; however, some data on HID lamps are available from a U.S. Department of Energy report [5]. Annual fluorescent ballast data are available from the U.S. Census Bureau's Current Industrial Reports, MQ335C (formerly MQ36C) [3]. The Census Bureau also collected

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[3] Commissioning involves reviewing design documentation, verifying installation, verifying testing of equipment and system performance, training building operators, and analyzing the operation of an efficient lighting system.

[4] Group relamping is less important for incandescent lighting since incandescents lamps have shorter lifetimes and less lumen depreciation than do fluorescent or HID lamps.

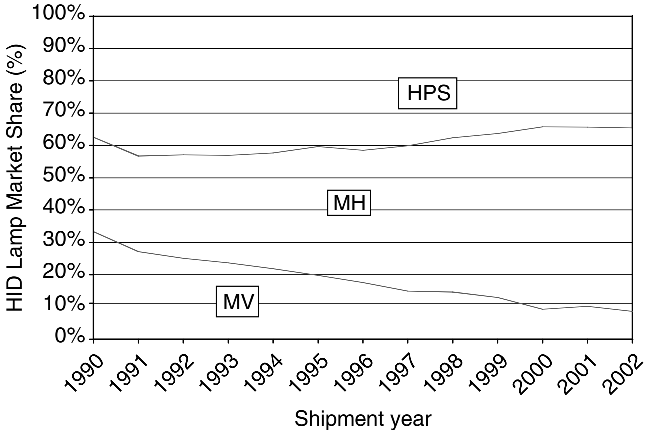

FIGURE 7.2 Total U.S. HID lamp shipments by type, 1990–2002. (From U.S. Department of Energy.)

data on electric lighting fixtures through 2001, which are still available on their website as MA335L (formerly MA36L).

Mercury vapor lamps were the first HID lamps, entering the market in the 1930s, and came into common use for outdoor lighting. Even in the early 1970s, nearly all HID lamps were MV. They were replaced by HPS lamps, which were first introduced in the 1960s and became common in street and roadway lighting because of the cost savings from their higher energy efficiency. Metal halide lamps, introduced into the market just after HPS lamps, have more recently become popular for area lighting and some interior applications as a "white light" source with better color rendering than HPS lamps. Mercury vapor lamp usage has declined considerably, although it persists in some areas for street lighting, rural security lighting, and landscape lighting.

As shown in Figure 7.2, the percentage of total HID shipments comprised by MV lamps declined from 33% in 1990 to 9% in 2002, as shown in Figure 7.1. During that period, MH lamp shipments increased, while HPS lamp shipments remained relatively constant.

The fluorescent ballast market has evolved considerably in recent years and has experienced a growing percentage of electronic ballasts. Figure 7.3 shows the evolution of the fluorescent ballast market for

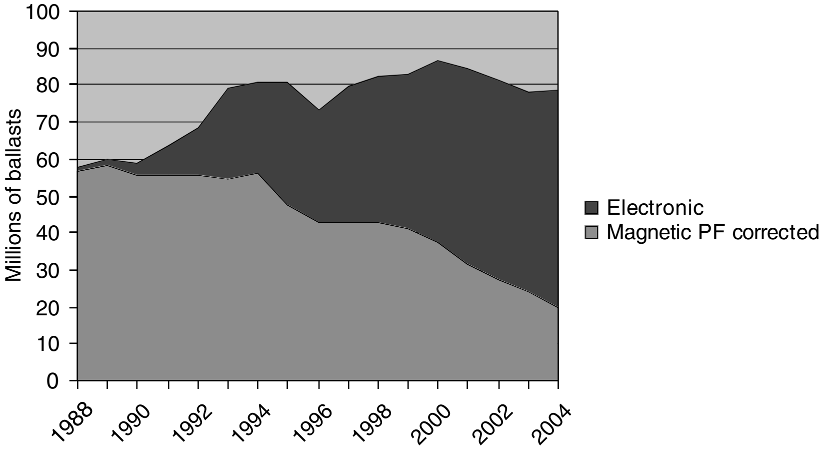

FIGURE 7.3 U.S. fluorescent ballast shipments, 1988–2004. (From U.S. Census Bureau, Current Industrial Reports for Fluorescent Lamp Ballasts, 1988–2004)http://www.census.gov/cir/www/335/mq335c.html.

ballasts used in the commercial and industrial sectors (electronic and magnetic power-factor corrected ballasts). Electronic ballasts accounted for less than 3% of total ballast sales for these sectors in 1987, but shipments began to grow in the early 1990s, partly through utility rebate and other incentive programs. The percentage of the market comprised by electronic ballasts has grown rapidly, going from 35% in 1997 to 67% in 2004. This strong increase in the sale of electronic ballasts has been accompanied by a significant decrease in price.

As discussed in Section 7.6, new ballast efficiency standards began to affect the market in 2005, prohibiting the manufacture of magnetic fluorescent ballasts destined for the fluorescent luminaire market, with their production for this market required to cease in 2005 and sales to stop in mid-2006. Magnetic ballasts for the replacement ballast market (for existing fixtures) can still be sold until mid-2010.

7.6 Lighting Efficiency Standards and Incentive Programs

In U.S., there are various drivers to development and promotion of efficient lighting technologies. Research and development is an ongoing process for manufacturers of lighting equipment and they regularly refine existing technologies and introduce new products to the market. Developments in the electronics industry are likely to foster innovations in lighting technologies as well. Federal national laboratories have been involved in efficiency-related research and market transformation programs, and have been especially active in developing and promoting technologies such as electronic ballasts and fluorescent torchieres. In the 1990s, electric utility demand-side management (DSM) incentives, such as customer rebates and information programs, actively promoted efficient lighting technologies. Although utility deregulation reduced the involvement of utilities in the promotion of efficient technologies, subsequent electricity supply crises and the slowdown of deregulation have contributed toward the return of some DSM incentives.

Government regulations are important policy tools for encouraging energy efficiency. At the federal level, lamps and ballasts are regulated through equipment standards and labeling requirements. Within states, lighting levels are regulated through building codes. Federal and state governments also sponsor nonregulatory information and incentive programs for efficient lighting. The U.S. Environmental Protection Agency (EPA) and Department of Energy (DOE) sponsor Energy star®, an information and voluntary incentive program that has designed energy-efficiency specifications for a variety of products. The Energy star® program also provides design guidelines and assistance to businesses and homeowners who are interested in reducing their buildings' energy consumption, including lighting energy, and helps them to set savings goals. Federal government and state governments also promote lighting efficiency through procurement policies.

Three U.S. laws specifically mandate the use of efficient lighting components: the National Appliance Energy Conservation Amendments[5] of 1987 (NAECA), the Energy Policy Act of 1992 (EPAct 1992)[6], and the Energy Policy Act of 2005 (EPAct 2005).[7] Some states have also adopted standards on certain lighting products. In addition to standards on specific equipment, states may regulate lighting through building codes that have maximum lighting consumption limits (W/square ft. or W/square meter). EPAct 1992 requires states to adopt certain building code provisions for new construction or substantial renovations, as discussed below. Many states have complied, and a few states have building codes that exceed the EPAct 1992 requirements.

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[5] NAECA amended the National Energy Conservation and Policy Act (NECPA) of 1978 that authorized the U.S. Department of Energy (DOE) to set mandatory energy-efficiency standards for various products.

[6] Public Law 102–486.

[7] Public Law 109-58.

NAECA regulates the sale of ballasts that drive fluorescent lamps. Ballasts sold for use in commercial or industrial lighting installations are required to meet or exceed minimum ballast efficacy factors (BEF) values.[8] The original ballast efficiency standards that took effect in 1991 applied to certain fluorescent lamp ballasts that operate T12 lamps. These standards required ballasts to have efficacies greater than or equal to those of energy-efficient magnetic ballasts. Updated standards, which essentially require the efficiencies of electronic ballasts, apply to ballasts manufactured after July 1, 2005 and incorporated into luminaires by luminaire manufacturers on or after April 1, 2006. Ballasts used for replacement (existing buildings) have until June 30, 2010 to meet the standard levels. The 5-year time delay was designed to allow building owners to retrofit their spaces with uniform systems rather than replacing them one by one as ballasts burn out. In addition, EPAct 2005 contains provisions that add BEFs for ballasts that drive reduced-wattage T12 lamps, taking effect in 2010. End users who cannot use electronic fluorescent ballasts for technical reasons (primarily electronic interference with specialized equipment) may use T8 lamps with magnetic ballasts. These magnetic ballasts are specifically designed for use with T8 lamps; magnetic ballasts that operate T12 lamps draw different amperage than T8 magnetic ballasts.

EPAct 1992 mandated energy-efficiency standards for linear fluorescent lamps and incandescent reflector lamps sold in the U.S. that became effective in 1994 and 1995. Essentially, they require 4-ft., 8- and 8-ft. high output T12 fluorescent lamps to either be reduced-wattage lamps or use rare-earth phosphors to comply. Incandescent reflector lamp efficacies must essentially use halogen technology (or better) to comply, although there are a variety of exempted reflector lamp categories. Two exempted lamp types, bulged reflector (BR) and elliptical reflector (ER) lamps, have gained in market share since the standards took effect in 1995. BR and ER lamps employ variations on reflector geometry to more efficiently focus light, although their efficacies are not as high as those of reflector lamps using halogen technology. There have been discussions at both the federal and state levels on incorporating ER and BR lamps into existing lamp standards. In 2006, DOE began a rulemaking to amend energy conservation standards for residential, commercial and industrial general service fluorescent lamps, incandescent reflector lamps and general service incandescent lamps.

In addition, EPAct 1992 mandated labeling for linear fluorescent, compact fluorescent, general service incandescent and incandescent reflector lamps. Labeling requirements took effect in 1994 and 1995. Compact fluorescent and incandescent lamps have their labels on the packaging; for linear fluorescents, the label is etched onto the lamp.

EPAct 2005 contains new regulations for several lighting products.

- Medium-based CFLs must meet the Energy star® specifications (version 2, August 2001), for minimum initial efficacy, lumen maintenance at 1000 h, lumen maintenance at 40 % of rated life, rapid cycle stress test, and lamp life. In addition, DOE may add requirements that color quality (CRI), power factor, operating frequency, and maximum allowable start time meet Energy star® version 2 specifications. This regulation took effect in 2006.
- Illuminated exit signs must meet Energy star® specifications (version 2), which require each sign to operate at 5 W or less. Essentially, signs whose light source is LEDs (or another low wattage technology) comply while rather those containing incandescent or fluorescent lamps do not comply. This regulation took effect in 2006.
- Traffic signal and pedestrian modules must meet Energy star®; specifications (version 1.1) that require LED technology. This regulation took effect in 2006.
- Torchieres cannot operate with lamps that total more than 190 W, which eliminates halogen lamps but allows incandescent lamps. This regulation took effect in 2006.
- Beginning in 2007, ceiling fan light kits using screw-base lamps must be packaged with lamps that meet the Energy star® requirements (version 2) for CFLs, or meet the Energy star® requirements (version 4) for residential light fixtures. DOE may also set standards for ceiling

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[8] BEF is defined as ballast factor × 100 divided by input watts.

fan light kit niche products, such as those with candelabra base or halogen lamps, to take effect in 2007.

- Beginning in 2008, MV lamp ballasts cannot be manufactured or imported.

Information and updates to U.S. lighting equipment standards are available on DOE's website http://www.eere.energy.gov/buildings/appliance_standards.

Some states have enacted standards on lighting products that are not covered by DOE efficiency standards. For information on state standards, see the Appliance Standards Awareness Project website http://www.standardsasap.org/. Note that in the U.S. federal regulatory coverage of a product preempts states from setting standards on that product, hence some state lighting equipment standards are affected by the new EPAct 2005 standards.

EPAct 1992 required states to adopt a building energy code at least as stringent as the ASHRAE/IESNA[9] 90.1-1999 building code by July 15, 2004 [1,4].[10,11] Legislation that provides compliance with this statue varies from state to state. Some states have adopted their own building codes, which may contain provisions more stringent than those in ASHRAE/IESNA 90.1-1999 or 2001, while others have not yet upgraded their building codes. The 2003 International Code Council's energy code contains a reference to ASHRAE/IESNA 90.1-2001. This energy code, named the International Energy Conservation Code (IECC), is used by many states to meet the EPAct building energy code requirement. These codes apply to new construction or additions and to new equipment in existing spaces. For information on DOE's Building Codes Program, see www.energycodes.gov. For more information on the status of state building codes, see the Building Codes Assistance Project website, http://www.bcap-energy.org. The ASHRAE/IESNA 90.1-1999 standard may be ordered from ASHRAE (http://www.ashrae.org/). The IECC 2003 code may be ordered through ICC (http://www.iccsafe.org/).

Various states and local jurisdictions have developed "dark sky" ordinances that regulate outdoor lighting. These regulations may include limits on light trespass, sky glow, pole heights, or energy use, as well requiring automatic shutoff controls. For more information, see the International Dark Sky Association website, http://www.darksky.org/ordsregs/odl-regs.html. ASHRAE/IESNA 90.1, IECC, and California's Title 24 building codes have outdoor lighting provisions related to energy use that have evolved from very simple to more complex as the standards have been revised. One innovation in the latest revision of California Title 24 establishes four exterior lighting zones and sets power limits per zone according to how much light is needed. Lighting zone 1 (parks, recreation areas, wildlife preserves) is designated as "dark"; lighting zone 2 (rural areas) is designated for low ambient illumination; lighting zone 3 (urban areas) is designated for medium ambient illumination; and lighting zone 4 is designed for high ambient illumination. Methods for calculating the alllowed lighting power levels are specified in the code for each zone.

Programs that promote consumer purchase of energy-efficient technology through setting voluntary energy-efficiency targets, notably the Energy star® program conducted by the U.S. Environmental Protection Agency (EPA) and DOE, have been an effective incentive for energy-efficient lighting. As noted above, some Energy star® qualifications have become the basis for lighting standards in EPAct 2005, for the FEMP procurement guidelines described below, and for various state standards and public utility incentive programs. Information on product qualifications may be found on the Energy star® website www.energystar.gov.

Lighting products for federal buildings often must meet specific standards or procurement guidelines. DOE's Federal Energy Management Program (FEMP) has energy efficiency recommendations for government procurement for several lighting products, including lamps, ballasts, exit signs,

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[9] ASHRAE = American Society of Heating Refrigerating and Air Conditioning Engineers. IESNA = Illuminating Engineering Society of North America.

[10] As updated by the Department of Energy's reference in the Federal Register, July 15, 2002.

[11] The original ASHRAE Standard 90 was published in 1975 and revised editions were published in 1980, 1989, 1999, 2001, and 2004.

TABLE 7.2 Cost-Effectiveness of Efficient Lighting Technologies

Product	Baseline Technology	Efficient Technology	Cost of Conserved Energy (CCE) in c/kWh
Torchiere (residential)	Incandescent	Fluorescent	6.8
Fluorescent lamp/ballast (commercial)	Current practice[a]	High performance T8 with high performance ballast	1.1

[a] F40T12 reduced wattage lamp (34 W) with magnetic ballast (15% market share); standard T8 lamp with electronic ballast (85% share).

luminaires, and controls. Many of FEMP's recommendations for energy using products match the qualifications for the Energy star® products, and must be selected when life-cycle costs warrant such selection. For more information on the equipment procurement product energy-efficient recommendations, see http://www.eere.energy.gov/femp/.

7.7 Cost-Effectiveness of Efficient Lighting Technologies

The energy savings from energy-efficient lighting systems provide energy cost savings over the lifetime of the equipment. In some cases, maintenance savings also accrue because the lighting systems have longer useful lives. Consumers and decision-makers weigh these costs against the higher first cost of the efficient technologies. Consumer choices regarding what types of efficient lighting technologies to purchase also depend on the lighting quality provided by the alternative system.

To fully assess the financial costs and benefits of an alternative lighting system, required sophisticated economic analysis is required. In addition to the costs of equipment and installation, one should consider energy, relamping, and maintenance costs over the life of the lighting system, as well as disposal costs. Evaluation of lighting quality and its potential economic impacts on user satisfaction and productivity is also important.

A study for the National Commission on Energy Policy (NCEP) estimated their costs and energy savings of appliances and lighting equipment relative to baseline designs [15]. For a number of products, it determined the efficiency level that provides users with the lowest life-cycle cost over the equipment lifetime. Table 7.2 lists the selected efficiency levels along with their associated cost of conserved energy (CCE) for consumers. CCE is an expression of the extra first cost incurred to save a unit of energy, with units of cents per 1 kWh. The CCEs in Table 7.2 are calculated assuming that equipment is purchased in the year 2010. The CCE may be compared to expected electricity prices. Long term forecasts for average residential electricity prices for the period studied are 8.5–9.0 cents/kWh [7], which is higher than the CCE for fluorescent torchieres, making the investment cost-effective. For the commercial sector lighting, marginal electricity prices are forecast between 6.8 and 7.5 cents/kWh [7], much higher than the CCE for high-performance T8 lamp/ballast systems.

7.8 Conclusion

In this chapter, we have provided an overview of energy-efficient lighting design practices as well as both traditional and newer, more efficient lighting technologies. Lighting is an important electrical end use in all sectors in the United States, and accounts for approximately one-quarter of national electricity use for commercial plus residential buildings. Through the use of more efficient lighting technologies as well as advanced lighting design practices and control strategies, there is significant potential for saving electricity, reducing consumer energy costs, and reducing the emission of greenhouse gases associated with electricity production. In addition, efficient lighting technologies and design can improve the quality of light in both the workplace and the home.

Glossary

Ballast:	A lamp ballast is an electrical device used to control the current provided to the lamp. In most discharge lamps, a ballast also provides the high voltage necessary to start the lamp.
Ballast Factor:	the fractional (luminous) flux of a fluorescent lamp operated on a ballast compared to the flux when operated on the standard (reference) ballast specified for rating lamp lumens.
Color Rendering Index (CRI):	A measure of how surface colors appear when illuminated by a lamp compared to how they appear when illuminated by a reference source of the same color temperature. For color temperature above 5000 K, the reference source is a standard daylight condition of the same color temperature; below 5000 K, the reference source is a blackbody radiator.
Color Temperature:	The color of a lamp's light expressed in degrees Kelvin (K). The concept of color temperature is based on the fact that the emitted radiation spectrum of a black-body radiator depends on temperature alone. The color temperature of a lamp is the temperature at which an ideal blackbody radiator would emit light that is the same color as the light of the lamp.
Efficacy:	The ratio of the amount of light emitted (lumens) to the power (watts) drawn by a lighting system. The unit used to express efficacy is lumens per watt (LPW). Efficacy may be expressed as *lamp efficacy*, using the nominal wattage of the lamp, or as *system efficacy*, using the system watts that include the ballast losses.
Lumen Maintenance:	The extent to which a lamp sustains its lumen output (and therefore efficacy) over time.

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8

Energy Efficient Technologies: Major Appliancies and Space Conditioning Equipment

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8.1 Introduction

Residential energy consumption accounts for approximately 37% of electricity use and 23% of natural gas use in the United States. In total, U.S. households spent more than $140 billion for home energy in 2001 and the average U.S. household spent almost $1,400 on its energy bill (Energy Information Administration (EIA) 2005a).

Major appliances and space conditioning equipment (which includes furnaces, boilers, heat pumps, and air conditioners) accounted for approximately 70% of U.S. residential energy consumption in 2003 (see Table 8.1).[1]

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[1] This chapter covers the equipment listed in Table 8.1. It does not cover the many other small appliances that have come to play a significant role in U.S. homes.

TABLE 8.1 U.S. Residential Energy Consumption by End Use in 2003

End Use	Electricity Use (EJ/yr)	Natural Gas Use (EJ/yr)	Other Energy Use (EJ/yr)[a]	Total Primary Energy Use (EJ/yr)	Share of Total Residential Primary Energy Use (%)
Space heating	0.46[b]	3.70	1.54	6.81	32.0
Space cooling	0.67[c]	0.00	0.00	2.18	10.2
Water heating	0.37	1.17	0.17	2.53	11.9
Refrigeration	0.40	0.00	0.00	1.30	6.1
Cooking	0.10	0.21	0.03	0.57	2.7
Clothes dryers	0.24	0.07	0.00	0.85	4.0
Freezers	0.13	0.00	0.00	0.42	2.0
Clothes washers	0.03	0.00	0.00	0.10	0.5
Dishwashers	0.02	0.00	0.00	0.08	0.4
Subtotal	2.42	5.15	1.74	14.8	69.6
Lighting	0.78	0.00	0.00	2.60	12.2
All other uses	1.17	0.10	0.17	3.89	18.3
Total	4.37	5.25	1.90	21.3	100

[a] Includes distillate, liquefied petroleum gas (LPG), and wood.

[b] Includes 3/4 of total furnace fan electricity use.

[c] Includes 1/4 of total furnace fan electricity use.

Source: From Energy Information Administration (EIA). 2005a. *Household Energy Consumption and Expenditures 2001*, U.S. Department of Energy, Washington, DC; Energy Information Administration (EIA). 2005b. *Annual Energy Outlook 2005*, U.S. Department of Energy, Washington, DC.

Reducing the energy consumption of residential appliances and space conditioning equipment depends on replacing older equipment with the much more efficient models that are now available and on continuing to design even more energy-efficient appliances. National energy efficiency standards for appliances have driven efficiency improvements over the last 20 years, and appliances have become significantly more efficient as a result. Further improvement of appliance efficiency represents a significant untapped technological opportunity.

8.2 Description of Major Appliances and Space Conditioning Equipment

8.2.1 Refrigerator-Freezers and Freezers

Refrigerators, refrigerator-freezers, and freezers keep food cold by transferring heat from the air in the appliance cabinet to the outside. A refrigerator is a well-insulated cabinet used to store food at 0°C or above; a refrigerator-freezer is a refrigerator with an attached freezer compartment that stores food below -13°C; and a standalone freezer is a refrigerated cabinet to store and freeze foods at -18°C or below. Almost all refrigerators are fueled by electricity. The refrigeration system includes an evaporator, a condenser, and a compressor. The system uses a vapor compression cycle, in which the refrigerant changes phase (from liquid to vapor and back to liquid again) while circulating in a closed system. The refrigerant absorbs or discharges heat as it changes phase. Although most refrigerants and insulating materials once contained chlorofluorocarbons (CFCs), all U.S. models sold after January 1, 1996, are CFC-free.

Almost all households have a refrigerator-freezer and many have more than one. Thirty-two percent of households had stand alone freezers in 2001. Ambient temperature is a significant determinant of the energy consumed by these appliances, but user behavior has relatively little effect on the energy consumption of these appliances (Meier 1995).

8.2.2 Water Heaters

A water heater is an appliance that is used to heat potable water for use outside the heater upon demand. Water heaters supply water to sinks, bathtubs and showers, dishwashers, and clothes washing machines. Most water heaters in the United States are storage water heaters, which continuously maintain a tank of water at a thermostatically controlled temperature. The most common storage water heaters consist of a cylindrical steel tank that is lined with glass in order to prevent corrosion. Most hot water tanks manufactured today are insulated with polyurethane foam and wrapped in a steel jacket. Although some use oil, almost all storage water heaters are fueled by natural gas (or LPG) or electricity.

Rather than storing water at a controlled temperature, instantaneous water heaters heat water as it is being drawn through the water heater. Both gas-fired and electric instantaneous water heaters are available. Instantaneous water heaters are quite popular in Europe and Asia. Although they are not commonly used in the United States, their presence does seem to be increasing. No heaters of this type are manufactured in the United States.

Like refrigerators, water heaters are present in almost all U.S. households. Approximately 54% of households have gas-fired water heaters, and approximately 38% have electric water heaters. Hot water use varies significantly from household to household, mostly due to differences in household size and occupant behavior.

8.2.3 Furnaces and Boilers

Furnaces and boilers are major household appliances used to provide central space heating. Both fuel-burning and electric furnaces and boilers are available. A typical gas furnace installation is composed of the following basic components: (1) a cabinet or casing; (2) heat exchangers; (3) a system for obtaining air for combustion; (4) a combustion system including burners and controls; (5) a venting system for exhausting combustion products; (6) a circulating air blower and motor; and (7) an air filter and other accessories. (Furnaces that burn oil and liquid petroleum gas (LPG) are also available, though not as common.) In an electric furnace, the casing, air filter, and blower are very similar to those used in a gas furnace. Rather than receiving heat from fuel-fired heat exchangers, however, the air in an electric furnace receives heat from electric heating elements. Controls include electric overload protection, contactor, limit switches, and a fan switch. Furnaces provide heated air through a system of ducts leading to spaces where heat is desired. In a batter system, hot water or steam is piped to terminal heating units placed throughout the household. The boiler itself is typically a pressurized heat exchanger of cast iron, steel, or copper in which water is heated.

Natural gas was the primary space-heating fuel in approximately 55% of U.S. households in 2001, and electricity was the primary space-heating fuel in 29% of households. The amount of energy consumed by a household for space heating varies significantly with climate and various household characteristics.

8.2.4 Central and Room Air Conditioners

A central air conditioning (AC) system is an appliance designed to provide cool air to an enclosed space. Typically, central AC systems consist of an indoor unit and an outdoor unit. The outdoor unit contains a compressor, condenser (outdoor heat exchanger coil), condenser fan, and condenser fan motor; the indoor unit consists of an evaporator (indoor conditioning coil) and a flow control device (a capillary tube, thermostatic expansion valve, or orifice) residing either in a forced-air furnace or an air handler. Refrigerant tubing connects the two units. A central AC system provides conditioned air by drawing warm air from the space and blowing it through the evaporator; as it is passing through the evaporator, the air gives up its heat content to the refrigerant. The conditioned air is then delivered back to the space (via a ducted system) by the blower residing in the furnace or air handler. The compressor takes the vaporized refrigerant aiming out of the evaporator and raises it to a temperature exceeding that of the outside air. The refrigerant then passes on to the condenser (outside coil), where the condenser fail blows outside air over it, gives up its heat to the cooler outside air, and condenses. The liquid refrigerant is then taken by the flow control device and its pressure and temperature are reduced. The refrigerant reenters the evaporator, where the refrigeration cycle is repeated.

Unlike the two-unit, central AC system, a room air conditioner is contained within one cabinet and is mounted in a window or a wall so that part of the unit is outside and part is in. The two sides of the cabinet are typically separated by an insulated divider wall in order to reduce heat transfer. The components in the outdoor portion of the cabinet are the compressor, condenser, condenser fan, fan motor, and capillary tube. The components in the indoor portion of the cabinet are the evaporator and evaporator fan. The fan motor drives both the condenser and evaporator fans. A room AC provides conditioned air in the same manner described for a central AC system.

Approximately 78% of U.S. households had an AC system in 2001. Central AC systems (including heat pumps) are used in 54% of households; room ACs are used in 23% of households.

8.2.5 Heat Pumps

Unlike air conditioners, which provide only air source space cooling, heat pumps use the same equipment to provide both space heating and cooling. An air source heat pump draws heat from the outside air into a building during the heating season and removes heat from a building to the outside during the cooling season. An air source heat pump contains the same components and operates in the same way as a central AC system but is able to operate in reverse as well, in order to provide space heating. In providing space heat, the indoor coil acts as the condenser while the outdoor coil acts as the evaporator. When the outside air temperature drops below 2°C during the heating season, a heat pump will utilize supplementary electric-resistance backup heat. Heat pumps were used in approximately 11% of U.S. households in 2001. The energy consumption of heat pumps varies according to the same user characteristics discussed above for AC systems. A more detailed analysis of heat pumps is presented in Chapter 9.

8.2.6 Clothes Washers

A clothes washer is an appliance that is designed to clean fabrics by using water, detergent, and mechanical agitation. The clothes are washed, rinsed, and spun within the insulated cabinet of the washer. Top-loading washers move clothes up and down, and back and forth, typically about a vertical axis. Front-loading machines move clothes around a horizontal axis. Electricity is used to power an electric motor that agitates and spins the clothes, as well as a pump that is used to circulate and drain the water in the washer tub. A separate water heater is used to heat the water used in the washer (some clothes washers also have an internal electric water heater).

Approximately 79% of households had clothes washers in 2001. Most of the clothes washers sold in the United States are top-loading, vertical-axis machines. The majority of energy used for clothes washing (85%–90%) is used to heat the water. User behavior significantly affects the energy consumption of clothes washers. The user can adjust the amount of water used by the machine to the size of the load, and thereby save water and energy. Choosing to wash with cold water rather than hot water reduces energy consumption by the water heater. Similarly, rinsing with cold water rather than warm can reduce energy consumption. Energy consumption depends on how frequently the washer is used. The Department of Energy's test procedure assumes clothes washers are used 392 times a year on average.

8.2.7 Clothes Dryers

A clothes dryer is an appliance that is designed to dry fabrics by tumbling them in a cabinet like drum with forced-air circulation. The source of heated air may be powered either by electricity or natural gas. The motors that rotate the drum and drive the fan are powered by electricity. Approximately 57% of U.S. households had electric clothes dryers, and 16% had gas dryers in 2001.

8.2.8 Dishwashers

A dishwasher is an appliance that is designed to wash and dry kitchenware by using water and detergent. Typically in North America hot water is supplied to the dishwasher by an external water heater. In addition an internal electric heater further raises the water temperature within the dishwasher. Electric motors pump water through spray arms impinging on the kitchenware in a series of wash and rinse cycles. An optional drying function is also enabled by electric heaters and sometimes a fan. In recent years, some dishwashers incorporate soil sensors that determine when the dishes are clean and the washing cycle can be stopped. Approximately 53% of U.S. households had dishwashers in 2001.

8.2.9 Cooktops and Ovens

A cooktop is a horizontal surface on which food is cooked or heated from below; a conventional oven is an insulated, cabinet like appliance in which food is surrounded by heated air. When a cooktop and an oven are combined in a single unit, the appliance is referred to as a range. Both gas and electric ranges are available. Cooktops and ovens are present in almost all households. Almost 60% of households use electric cooktops and ovens, and the remaining 40% of households use gas cooktops and ovens.

In a microwave oven, microwaves directed into the oven cabinet cause water molecules inside the food to vibrate. Movement of the water molecules heats the food from the inside out. The fraction of households with microwave ovens has increased dramatically in recent years.

8.3 Current Production

Table 8.2 shows the number of various appliances that was shipped by manufacturers in 1995 and 2003. Shipments have been increasing for most of the major appliances.

8.4 Efficient Designs

State and federal standards requiring increased efficiency for residential appliances, utility programs, and labels (such as Energy star) have improved appliance efficiency dramatically since the late 1970s (Meyers et al. 2004). For example, the annual energy consumption (according to the DOE test procedure) of a new refrigerator in 2003 was less than half the consumption in 1980. Because of the slow turnover rate of appliances, however, the older, less efficient equipment remains in use for a long time. Promising design options for further improving the efficiency of residential appliances are discussed next.

TABLE 8.2 Shipments of Major Appliances and Space Conditioning Equipment in the U.S.

Product	1995 (Million Units)	2003 (Million Units)
Refrigerators[a]	7.65	10.02
Freezers	1.46	2.52
Water heaters	8.37	9.58
Clothes washers	6.08	8.15
Clothes dryers	4.99	7.34
Dishwashers	4.30	6.28
Gas furnaces	2.60	3.27
Heat pumps	1.03	1.63
Central air conditioners	3.11	3.75
Room air conditioners	3.96	8.22

[a] Standard size; reported shipments of compact refrigerators in 2003 were 1.46 million.

Source: Association of Home Appliance Manufacturers.

8.4.1 Refrigerators and Freezers

Relative to the 2001 U.S. federal efficiency standard, achieving a 15% energy use reduction for refrigerator-freezers is possible with the use of a high-efficiency compressor, high-efficiency motors for the evaporator and condenser fans, and adaptive defrost control. Models at this level of efficiency account for a modest market share in the U.S. achieving a 25% energy use reduction generally would require a reduction in load transmitted through the unit's walls and doors, which might require the use of vacuum panels.

8.4.1.1 Improved Fan Motors

The evaporator and condenser fans of large refrigerators are powered by motors. The most common motor used for this purpose is a shaded-pole motor. Large efficiency gains are possible in refrigerators and freezers by switching to electronically commutated motors (ECMs), also known as brushless permanent-magnet motors, which typically demand less than half as much power as shaded-pole motors.

8.4.1.2 Vacuum Insulation Panels

The use of vacuum insulation panels (VIP) can significantly reduce heat gain in a refrigerated cabinet and thereby decrease the amount of energy necessary to maintain a refrigerator or freezer at a low temperature. When using VIP, a partial vacuum is created within the walls of the insulation panels. Because air is conductive, the amount of heat transfer from the outside air to the refrigerated cabinet is reduced as the amount of air within the panels is reduced. Evacuated panels are filled with low-conductivity powder, fiber, or aerogel in order to prevent collapse. Energy savings associated with the use of vacuum panel insulation range from 10 to 20%. Vacuum panel technology still faces issues regarding cost and reliability before it can come into widespread use in refrigeration applications (Malone and Weir 2001).

8.4.2 Water Heaters

8.4.2.1 Gas-Fired Storage Water Heater

The current models of gas-fired storage water heaters have a central flue that remains open when the water heater is not firing. This leads to large off-cycle standby losses. It should be possible to dramatically reduce off-cycle losses with relatively inexpensive technical modifications to the water heater. Energy savings derived from models with these modifications are expected to be about 25% compared to the 2004 U.S. standards.

The amount of heat extracted from the fuel used to fire a gas appliance can be increased by condensing the water vapor in the flue gases. In a condensing storage water heater, the flue is lengthened by coiling it around inside the tank. The flue exit is located near the bottom of the tank where the water is coolest. Because the flue gases are relatively cool, a plastic venting system may be used. A drain must be installed in condensing systems. Energy savings associated with the use of a gas-fired condensing water heater are approximately 40% compared to the 2004 efficiency standard. At this time, the high cost of the water heater results in a payback time that exceeds the typical lifetime of a water heater, but it is reasonable to assume that the cost could be reduced to the point that the water heater would be cost-effective. In applications with heavy hot water use, such as laundromats or hotels, they may already be cost-effective. Currently, a few companies produce condensing storage water heaters for commercial markets, and they are sometimes sold as combined water heater/space heating systems for residential use.

8.4.2.2 Heat Pump Water Heaters

Heat pumps used with water heaters capture heat from the surrounding air or recycle waste heat from AC systems and then transfer the heat to the water in the storage tank. In this way, less energy is used to bring the water to the desired temperature. The heat pump can be a separate unit that can be attached to a standard electric water heater. Water is circulated out of the water heater storage tank, through the heat pump, and back to the storage tank. The pump is small enough to sit on the top of a water heater but could be anywhere nearby. Alternatively, the heat pump can be directly integrated into the water heater. Research indicates that this technology uses 60%–70% less energy than conventional electric resistance water heaters. Field and lab tests have been completed for several prototypes. A few models are currently available for sale.

8.4.2.3 Solar Water Heaters

Technological improvements in the last decade have improved the quality and performance of both passive and active solar water heaters. Research indicates that, in general, solar water heaters use 60% less energy than conventional electric resistance water heaters. There are several types of solar water heaters commercially available today.

8.4.3 Furnaces

8.4.3.1 Condensing Furnaces

The efficiency of a conventional gas furnace can be increased by using an additional heat exchanger to capture the heat of the flue gases before they are expelled to the outside The secondary heat exchanger is typically located at the outlet of the circulating air blower, upstream of the primary heat exchanger. A floor drain is required for the condensate. A condensing furnace has an efficiency up to 96% annual fuel utilization efficiency (AFUE), well above the 80% AFUE rating of a standard noncondensing gas furnace. Condensing furnaces have been on the market since the 1980s and now constitute one-third of all gas furnace sales. They are particularly popular in colder areas of the United States, where the cost of heating is high. An early technical problem, corrosion of the secondary heat exchanger, has been resolved by the industry.

8.4.3.2 Integrated Water Heaters and Furnaces

Traditionally, water heating and space heating have required two separate appliances—a hot water heater and a furnace. Combining a water heater and a furnace into a single system can potentially provide both space heating and hot water at a lower overall cost. Integrated water and space heating is most cost-effective when installed in new buildings because gas connections are necessary for only one appliance rather than two.

Combination space- and water-heating appliances fall into two major classes: (1) boiler/tankless-coil combination units, and (2) water-heater/fancoil combination units. A great majority of boiler/tankless-coil combination units are fired with oil, whereas most water-heater/fancoil combination units are fired with natural gas. In the latter units, the primary design function is domestic water heating. Domestic hot water is circulated through a heating coil of an air-handling system for space heating. Usually the water heater is a tank-type gas-fired water heater, but instantaneous gas-fired water heaters can be used as well.

The efficiencies of these integrated systems are determined largely by the hot water heating component of the system. Compared to a system using a standard water heater or boiler, an integrated system using a condensing water heater or condensing boiler can reduce energy consumption by as much as 25%.

8.4.4 Central and Room Air Conditioners

8.4.4.1 Electric Variable-Speed Air Conditioning

Variable-speed central air conditioners use ECMs, which are more efficient than the induction motors used in a single-speed system. In addition, the speed of the ECM can be varied to match system capacity more precisely to a building load. Cycling losses, which are associated with a system that is continually turned off and on in order to meet building load conditions, are thus reduced. Unlike induction motors, ECMs retain their efficiency at low speeds; consequently, energy use is also reduced at low-load conditions. A variable-speed AC system uses approximately 40% less energy than a standard single-speed AC system. Although these AC systems are now available from major manufacturers, they account for a small fraction of sales.

8.4.4.2 Electric Two-Speed Air Conditioning

Two-speed induction motors are not as efficient as variable-speed ECMs, but they are less expensive. Like variable-speed air conditioners, two-speed air conditioners reduce cycling losses. When two-speed induction motors are used to drive compressor and fans, the system can operate at two distinct capacities. Cycling losses are reduced because the air conditioner can operate at a low speed lo meet low building loads. In some models, two-speed compressors are coupled with variable-speed indoor blowers to improve system efficiency further. A two-speed AC system reduces energy consumption by approximately one-third. Although these AC systems are available from several major manufacturers, they account for a small fraction of sales.

8.4.4.3 Room Air Conditioners

The most efficient room air conditioners have relatively large evaporator and condenser heat-exchanger coils, high-efficiency rotary compressors, and permanent split-capacitor fan motors. Compared to standard room ACs, highly-efficient room ACs reduce energy consumption by approximately 25%. Such room ACs are available from several manufacturers. Units with Energy star designation, which must exceed federal minimum efficiency standards by 10%, accounted for 35% of sales in 2004.

8.4.5 Clothes Washers and Dryers

8.4.5.1 Horizontal-Axis Washers

Although horizontal-axis clothes washers dominate the European market, the vast majority of clothes washers sold in the United States are top-loading, vertical-axis machines. However, this is expected to change by 2007 when more stringent minimum efficiency regulations on clothes washers will take effect. Horizontal-axis washers, in which the tub spins around a horizontal axis, use much less water than their vertical-axis counterparts, and less hot water is therefore required from water heaters. As mentioned earlier, the majority of energy used for clothes washing is used for heating water, so a significant amount of energy can be saved by using horizontal-axis washers. Research has indicated that horizontal-axis washers are more than twice as efficient as vertical-axis washers of comparable size (U.S. Department of Energy 2000).

8.4.5.2 High-Spin-Speed Washers

Clothes washers can be designed so that less energy is required to dry clothes after they have been washed. Extracting water from clothes mechanically in a clothes washer uses approximately 70 times less energy than extracting the water with thermal energy in an electric clothes dryer. Thus, by increasing the speed of a washer's spin cycle, one can reduce the energy required to dry clothes.

Because gas clothes dryers require so much less energy than electric dryers, based on energy consumption including that consumed at the electric power station, energy savings are much more significant when a high-spin-speed washer is used with an electric dryer. In a vertical-axis clothes washer, an increase in spin speed from 550 to 850 rpm reduces moisture retention from 65 to 41%. In an electric dryer, this reduces the energy consumption by more than 40%. In a horizontal-axis washer, an increase in spin speed from 550 to 750 rpm reduces moisture retention from 65 to 47%; in an electric dryer, energy consumption is reduced by more than 30%. High-spin-speed washers have been common on European horizontal axis machines for some time, and are becoming more common in the U.S.

8.4.5.3 Microwave Dryers

In conventional clothes dryers, hot air passes over wet clothes and vaporizes the surface water. During the later stages of drying, the surface dries out and heat from the hot air must be transferred to the interior, where the remaining moisture resides. In contrast, in microwave drying, water molecules in the interior of a fabric absorb electromagnetic energy at microwave wavelengths, thereby heating the water and allowing it to vaporize. Several U.S. appliance manufacturers have experimented with microwave clothes dryers, and a few small companies have built demonstration machines. Issues of small metal objects heating, such as rivets, would need to be resolved before microwave clothes dryers are likely to be sold.

8.4.5.4 Heat Pump Dryers

A heat pump dryer is essentially a clothes dryer and an air conditioner packaged as one appliance. In a heat pump dryer, exhaust heat energy is recovered by recirculating all the exhaust air back to the dryer; the moisture in the recycled air is removed by a refrigeration–dehumidification system. A drain is required to remove the condensate; because washers and dryers are usually located side by side, a drain is generally easily accessible. Heat pump dryers can be 50%–60% more efficient than conventional electric dryers. Introduced in Europe in 1999, heat pump dryers are available both in the U.S. and Europe.

8.4.6 Cost-Effectiveness of Energy-Efficient Designs

The cost-effectiveness of energy-efficient designs for major appliances and space conditioning equipment depends on consumer energy prices and also on per-unit costs when new technologies are manufactured on a large scale. Therefore, the cost-effectiveness of such designs varies

A U.S study, conducted in 2004 for the National Commission on Energy Policy (NCEP) reviewed the literature on energy efficient designs for major appliances and space conditioning equipment and estimated their costs (in the year 2010) and energy savings relative to baseline designs (Rosenquist et al. 2004). For a number of products, it determined the efficiency level that provides users with the lowest life-cycle cost over the appliance lifetime. Table 8.3 lists the selected efficiency levels (expressed in terms of annual energy consumption in some cases), along with their associated cost of conserved energy (CCE) for consumers. The CCE in terms of dollars per kWh or MMBtu (gas) is an expression of the extra first cost incurred to save a unit of energy. Calculation of CCE requires application of a present worth factor (PWF) to spread the initial incremental cost over the lifetime of the equipment. The PWF uses a discount rate to effectively amortize costs over time. The CCEs for electric appliances in Table 8.3 are all below the average U.S. residential electricity price.

TABLE 8.3 Cost-Effectiveness of Efficient Designs for Selected Appliances and Space Conditioning Equipment

Product	Baseline Technology	Efficient Technology	Cost of Conserved Energy[a]
Refrigerator	484 kWh/yr	426 kWh/yr	4.9 c/kWh
Room air conditioner	9.85 EER	10.11 EER	5.2 c/kWh
Electric water heater	92 EF	Heat pump	3.9 c/kWh
Clothes washer[b]	3.23 kWh/cycle	Horizontal-axis and high spin speed (1.87 kWh/cycle)	5.0 c/kWh
Gas furnace[c]	80% AFUE	Condensing furnace (90% AFUE)	$9.30/MBtu

[a] The CCE may be compared to expected residential energy prices. In the U.S., long-term forecasts from the Department of Energy (as of 2005) place average prices in the range of 8.5–9.0 cents/kWh for electricity and $7.7–8.4/million Btu for natural gas.

[b] Includes the energy for water heating and drying associated with clothes washing. Refers to electric water heater and dryer. Baseline refers to the 1994 DOE standard level. Additional consumer benefits derive from reduction in water usage.

[c] The CCE value is a U.S. national average. In cold climates, the amount of saved energy is higher, so the CCE is lower by a third or more.

Sources: Rosenquist, G., McNeil, M., Iyer, M., Meyers, S., and McMahon, J. 2004. *Energy Efficiency Standards for Residential and Commercial Equipment: Additional Opportunities*. Lawrence Berkeley National Laboratory, Berkeley, CA. Report No. LBNL-56207; U.S. Department of Energy-Office of Building Research and Standards. 2000. Final Rule Technical Support Document (TSD): Energy Efficiency Standards for Consumer Products: Clothes Washers. U.S. Department of Energy, Washington, DC. Report No. LBNL-47462. http://www.eren.doe.gov/buildings/codes_standards/reports/cwtsd/index.html.

8.5 Conclusion

Residential appliances consume significant amounts of electricity and natural gas. This chapter described the basic engineering principles of the major appliances and space conditioning equipment as well as promising energy-efficient designs.

Significant potential energy savings are possible beyond the models typically sold in the marketplace today. Among the various end uses, energy savings range from 10 to 50%. Many of these efficient appliances appear to be cost-effective at currently projected manufacturing costs, with simple payback times that are shorter than the typical appliance lifetimes of 10–20 years. If costs of efficiency improvements decrease, or if future energy prices increase, more of the potential energy savings that are already technically possible will become economically attractive. In addition, future research is likely to identify additional technological opportunities to save energy.

Acknowledgments

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9

Heat Pumps

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9.1 Basic Principles

Heat pumps are one of the most underused means of conserving energy for heating and cooling of buildings. The basic components of a heat pump are a working fluid or refrigerant, a gas compressor, two heat exchangers, piping, controls and accessories which can provide either heating or cooling to a building space. In the heating mode, heat is extracted from a natural or waste heat source and transferred to the space while in the cooling mode, heat is removed from the building and discharged to a heat sink.

There are four basic types of heat pumps, named air-to-air, water-to-air, water-to-water, and earth-to-air. In an air-to-air heat pump system, heat is removed from indoor air and rejected to the outdoor air of a building during the cooling cycle, while the reverse happens during the heating cycle. Water can replace the outdoors air as the source or sink for the heat, depending on whether the unit is in the heating or cooling mode. Air-to-air heat pumps or air source heat pumps (ASHP) is typically roof top units either completely packaged or split packaged systems. Split package heat pumps are designed with an air-handling unit located inside the conditioned space while the condenser and compressor are packaged for outdoor installation on the roof. ASHP are best suited for mild climates such as the southeastern part of the U.S. and areas where natural gas is either unavailable or expensive. For details on sizing, as well as protecting heat pumps operating in the heating mode when the ambient air temperatures drops below freezing see Ref. [1]

In water source heat pumps, instead of air, water is used to transfer the heat between the building and the outside. Geothermal heat pumps (discussed in more details in Section 9.2) use energy from the ground soil or ground water as the source or sink. In winter a geothermal heat pump transfers thermal energy from the ground to provide space heating. In the summer the energy transfer process is reversed. The ground absorbs thermal energy from the conditioned space and cools the air in the building. A GHP benefits from a nearly constant ground temperature year round, which is higher on average than winter air temperatures and lower on average than summer air temperatures. The energy efficiency of a GHP is thus higher than that of conventional ASHP's and some are also more efficient than fossil fuel furnaces in the heating mode. The primary difference between an ASHP and a GHP is the investment in a ground loop for heat collection and rejection required for the GHP system. Whether or not the GHP is cost-effective relative to a conventional ASHP depends upon generating annual energy cost savings that are high enough for the extra cost of the ground loop.

Figure 9.1a and Figure 9.1b illustrate schematically the basic mode of operation for cooling and heating a building. Figure 9.2a shows the different steps of operation on a pressure–enthalpy diagram for an ideal cycle in the refrigeration mode. An ideal cycle consists of the following four steps:

1. An isothermal evaporation process during which the refrigerant is completely evaporated and produces a refrigeration effect given by $Q_{rf} = (h_1 - h_4)$ where h_1 and h_4 are the enthalpies of the refrigerant at state point 1 and 4 respectively.
2. An isotropic compression process from 1 to 2 during which a compressor isotropically compresses the vapor refrigerant from state point 1–2. The work input for this step is given by $W_c = (h_2 - h_1)$
3. A constant pressure condensation process from state point 2–3 during which the hot gaseous refrigerant is first cooled to its saturation point and then condensed into liquid. The heat during the process is rejected to water, ambient air or the ground. The heat rejection is given by $Q_{23} = (h_2 - h_3)$
4. A throttling process from 3 to 4 during which the refrigerant flows through a throttling device, such as an orifice, and its pressure is reduced to the evaporation pressure. A portion of the liquid flashes into vapor and enters the evaporator at state point 4. This is a constant enthalpy irreversible process and in the ideal cycle $h_3 = h_4$.

The *coefficient of performance* (COP) is a dimensionless index used to indicate the performance of a refrigerator or a heat pump.

- In the refrigeration mode

$$\mathrm{COP}_{\mathrm{ref}} = \frac{\text{Refrigeration effect}}{\text{Work input}} = \frac{h_1 - h_4}{h_2 - h_1}$$

- The COP of a heat pump that produces a useful heat input is given by

$$\mathrm{COP} = \frac{Q_{23}}{\text{Work input}}$$

For details on the design of individual components in a heat pump see refs. [1], [2], and [3] as well as publications of the American Society of Heating Refrigeration and Air Conditioning Engineering (ASHRAE e.g. Handbook of Refrigeration, 1998).

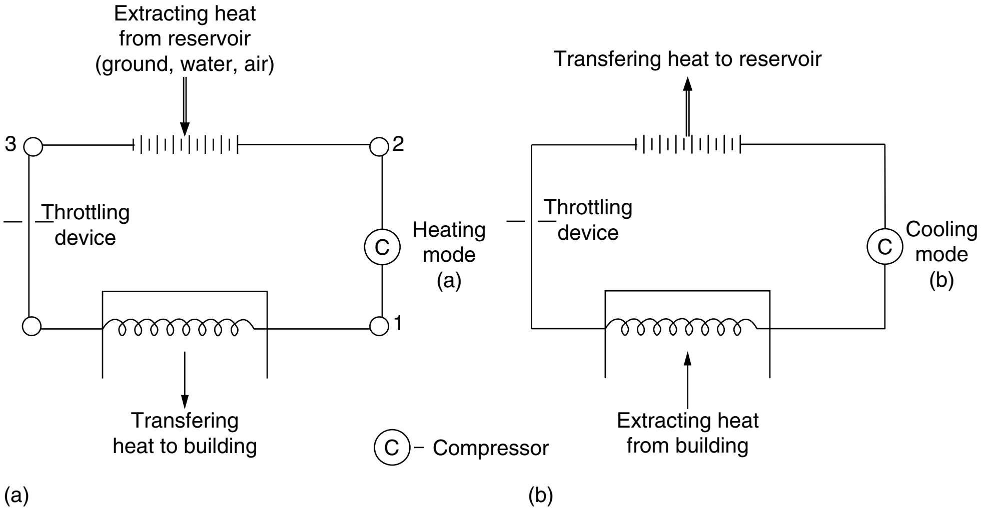


FIGURE 9.1 Schematic diagram of a heat pump in the heating mode (a) and cooling mode (b).

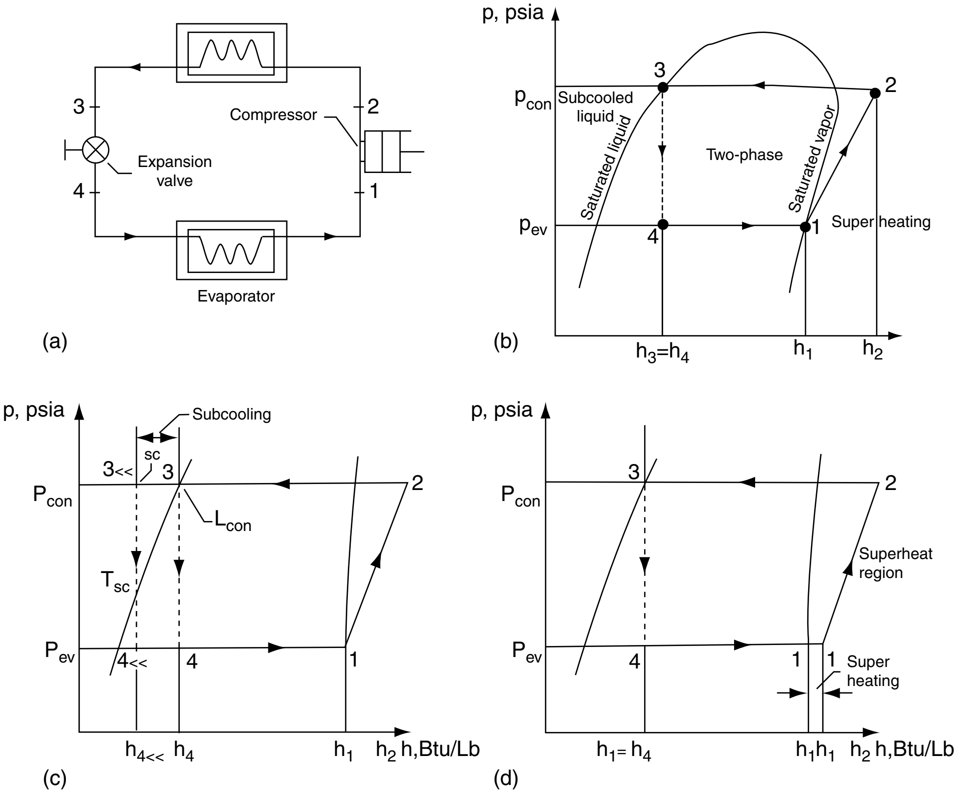


FIGURE 9.2 A single-stage ideal vapor compression refrigeration or heat pump cooling cycle; (a) schematic diagram (b) pressure enthalpy (p-h) diagram (c) subcooling, and (d) superheating.

At present, R22 is the most widely used working fluid in the air conditioning and heat pump industry, especially in residential unitary and air conditioning systems. However, the Montreal and Kyoto Protocols, as well as the U.S. Clean Air Act Amendments of 1990, which were based on the Montreal Protocol, forced the climate control industry to change its use of CFCs to HFCs. The phase-out of R22 compelled manufacturers to find alternatives. The air conditioning and refrigeration industry (ARI) started an R22 Alternative Refrigerants Evaluation Program to find and evaluate promising alternatives to the refrigerants containing ozone-depleting CFCs. The alternatives were to satisfy the requirements that refrigerants be: environmentally benign, nonflammable, chemically inert to avoid corrosion, nontoxic, and thermodynamically suitable. So far, no single refrigerant has been identified that can meet all of these requirements, but refrigerant mixtures are gaining importance as acceptable working fluids for future equipment. Ref. 4 presents the characteristics of mixtures and applications to heat pumps and other climate control equipment. The reader is referred to this book for detailed information on thermophysical properties of mixtures of refrigerants and their applications in climate control systems.

The COP of real heat pumps is less than that of the ideal OCP because there must be a temperature difference between the working fluid and the heat sink a s well as the heat source. Also, the work input to the compressor is larger than that shown for the ideal cycle. Methods to increase the COP are discussed below. *Variable-Speed and Two-Speed Heat Pumps.* Like central air conditioners, heat pumps can be made more efficient by the use of two-speed and variable-speed motors (see the earlier discussion of efficient central air conditioners). Both two-speed and variable speed air-source heat pumps are available. Compared to standard models, two-speed air-source heat pumps reduce energy consumption by approximately 27%, variable-speed air-source heat pumps reduce energy consumption by 35%, and two-speed ground-source heat pumps reduce energy consumption by 46%. Variable-speed and two-speed air-source heat pumps are made by the same companies that make variable speed and two-speed AC systems. Several manufacturers produce efficient air-source and two-speed ground-source heat pumps, but they account for a small fraction of all heat pump sales.

Gas-Fired Heat Pumps. Currently, all residential heat pumps are electric, but researchers have been developing gas heat pumps. The Gas Research Institute (GRI) and a private corporation jointly developed a natural gas, engine-driven, variable-speed heat pump in which the compressor is driven by an internal combustion spark-ignition engine and heat is recovered in the space-heating mode. This engine-driven heat pump was put on the market in 1994, but was withdrawn in the late 1990s due to lack of a maintenance infrastructure. In addition, the DOE has been funding the development of a gas-fired ammonia–water absorption-cycle heat pump. Gas-driven heat pumps have the potential to reduce heat pump energy consumption by approximately 35%–45%.

Distribution Systems. When assessing the efficiency of a space conditioning system, it is important to consider the efficiency of the distribution system as well as the appliance. It is not uncommon for air ducts to have distribution losses of 20%–40% due to conduction as well as leakage. Better insulation as well as more careful duct sealing can reduce these losses, In general, the most effective strategy for reducing distribution losses is to include the distribution system in the conditioned space so that any losses due to conduction or air leakage go directly into the space to be conditioned. This requires careful attention by the architect in the design of new buildings and is typically expensive as a retrofit measure.

9.2 Solar-Assisted Heat Pump Systems

A solar collector can improve the performance of either a liquid or an air system, but it adds complexity and expense. Low-temperature solar heat applied to one side of the heat-pump system (Figure 9.3) evaporates the low-pressure refrigerant liquid. The compressor then raises the pressure and temperature of the vapor which, when it condenses, gives off heat at a higher temperature than that at which heat was provided. When this temperature difference is less than 30°F–40°F (20°C), a good heat pump can provide heat at 105°F–115°F with a COP of about 3.5.

Solar-assisted heat-pump systems can be of several types[5]. One type uses liquid in the solar collector loop, water storage, and a water-to-water heat pump. Another type uses an air-to-air heat pump in conjunction with liquid-to-air heat exchangers and a liquid solar collector loop. Although solar-assisted heat pumps are normally used for heating only, the concept of a solar-assisted, double-bundle condenser, heat recovery chiller can be included in the heat-pump category[5]. In the summer, this system would operate as a conventional central station, chilled-water air-conditioning system; however, it could also operate at night under more favorable ambient conditions and possible reduced off-peak power rates, and store the “coolness” in its storage tank. In the winter, solar heat, as well as heat from people and lights in the interior zone of a large building, would create the load on the chiller evaporator. This system, suitable for large buildings, has the advantages of a heat pump without the complications associated with the reversing cycle features.

Heat pumps enhance the efficiency and lower the costs of the solar energy system by permitting the collectors to operate at low fluid temperatures with the heat pump boosting the air or water temperatures for delivery to the space at 105°F–115°F. The space-heating system must be designed for those low utilization temperatures. In large buildings the heat pump always utilizes the solar-heated water for a heat source to maintain high COP and capacity. A computer analysis is required to optimize the operating mode, collector and storage size, number of storage vessels, and control sequence. In some cases it may be more efficient to use all of the solar-heated hot water at low temperature as a source for the heat pump.

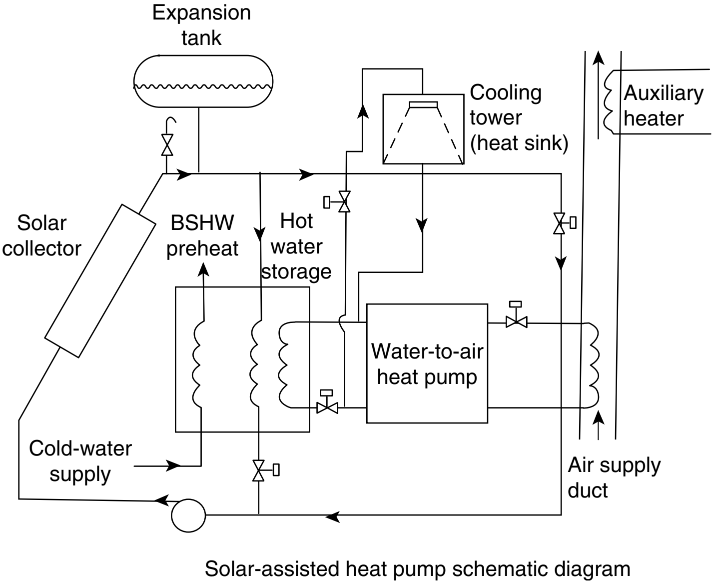


FIGURE 9.3 Schematic diagram for a solar collector assisted heat pump.

9.3 Geothermal Heat Pumps

Geothermal heat pumps (GHPS) are also called ground source heat pumps, earth source/earth coupled heat pumps, geothermal heating and cooling systems, direct exchange, and "geo" among others. Developing a common name was an early mission of the Geothermal Heat Pump Consortium (GHPC), a nonprofit industry association based in Washington, D.C. Their efforts led to creating a national "brand" or identity for this technology, now referred to as "GeoExchange."

Every geothermal system consists of three major elements: 1) a *geothermal heat pump* to move heat between the building and the fluid in the earth connection, 2) an *earth connection* for transferring heat between its fluid and the earth, and 3) a *distribution subsystem* for delivering heating or cooling to the building. To heat a building, the heat is extracted from the fluid in the earth connection by the geothermal heat pump and distributed through a system of air ducts. Cooler air from the building is returned to the geothermal heat pump, where it cools the fluid flowing to the earth connection Figure 9.4. The fluid is warmed again as it flows through the earth connection. The process is reversed to cool the building (Figure 9.5).

The ground loop may be installed either directly in the ground or through a well. The fluid could be either water or a refrigerant. Geothermal heat pumps can provide heating, cooling, and even hot water, at a significantly lower cost compared to conventional systems. However, geothermal systems installations usually cost two to three times more compared to conventional systems. These costs are higher because geothermal installations requiring working with three different kinds of specialists:

- Geothermal contractor
- Driller
- Loop installer.

Three types of configurations are used in installing a geothermal heat pump system. The type selected depends upon a number of factors including soil type, availability of a water source, the size of

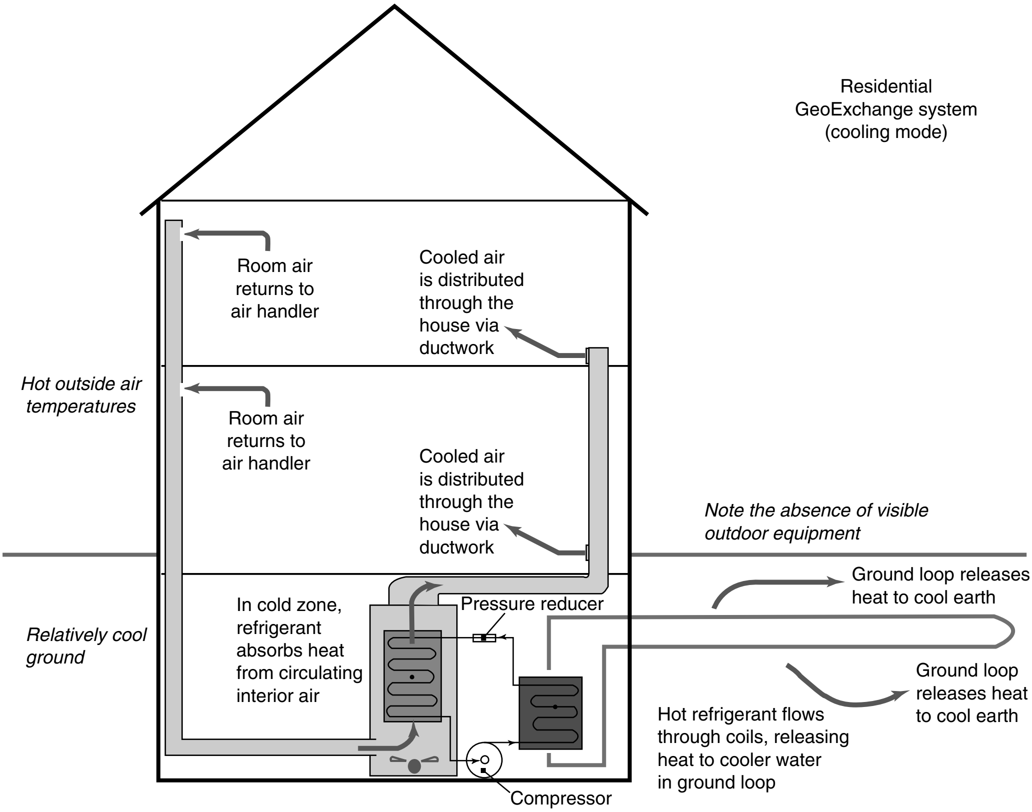


FIGURE 9.4 Example of a Residential Geothermal Heat Pump Configuration in the Summer Months (Drawing courtesy of the Geothermal Heat Pump Consortium.)

the installation, and the amount of land available. Loops may be installed horizontally or vertically in the ground, or submersed in a body of water. The type of loop configurations includes:

- Horizontal closed ground loop (Figure 9.6a)
- Vertical closed ground loop (Figure 9.6b)
- Pond or lake closed loop
- Open loop system
- Standing column well system

Geothermal heat pump systems offer a great deal of flexibility and according to the Geothermal Heat Pump Consortium (GHPC), these systems have been installed in thousands of commercial applications from guard shacks to high-rise office buildings, not to mention in thousands of houses and schools across the United States.

Geothermal heat pumps also offer significant benefits to customers willing to pay the higher upfront installation costs (Figure 9.7 through Figure 9.9). These benefits include:

- *Substantial cost savings*: Geothermal systems can save as much as 50% compared to air-source heat pumps and up to 45% over fossil-fuel (gas, propane, or oil) furnaces.
- *Economical rates*: Some utilities, such as Kansas City Power and Light, offer special, lower winter rates for geothermal customers, offering even more savings.

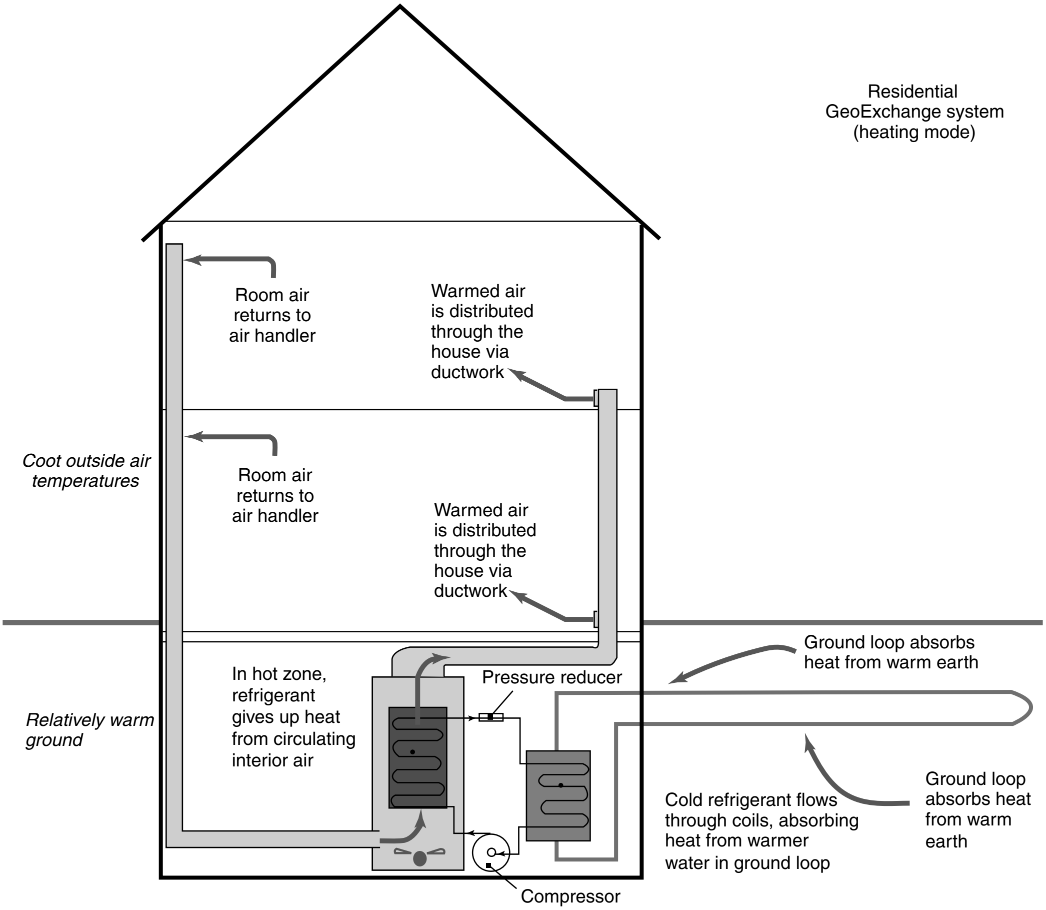


FIGURE 9.5 Example of a Residential Geothermal Heat Pump Configuration in the Winter Months (Drawing courtesy of the Geothermal Heat Pump Consortium.)

- *Environmentally Friendly*: Geothermal systems are a "renewable" energy source that encourages conservation of natural resources.
- *Financing*: Many utilities offer financing through either private financing or utility-sponsored loop leases.

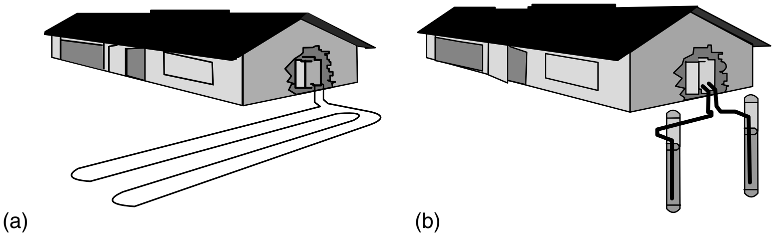
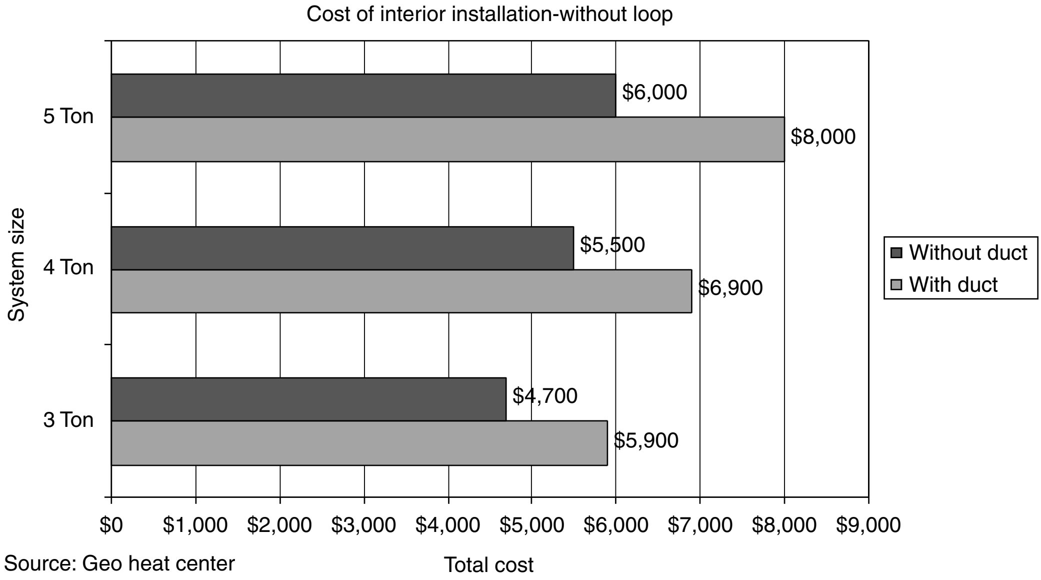


FIGURE 9.6 (a) Example of a Horizontal Loop Configuration in a Residential Installation. (b) Example of a Vertical Loop Configuration in a Residential Installation: Drawings courtesy of the Geothermal Heat Pump Consortium.

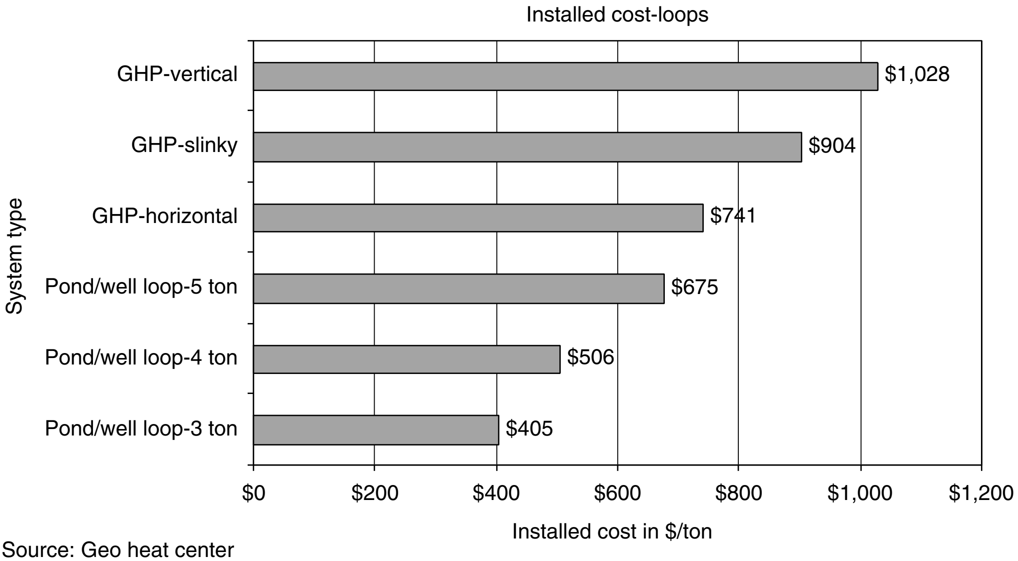


Source: Geo heat center

FIGURE 9.7 Average Interior Installation Costs for GHPs by System Size.

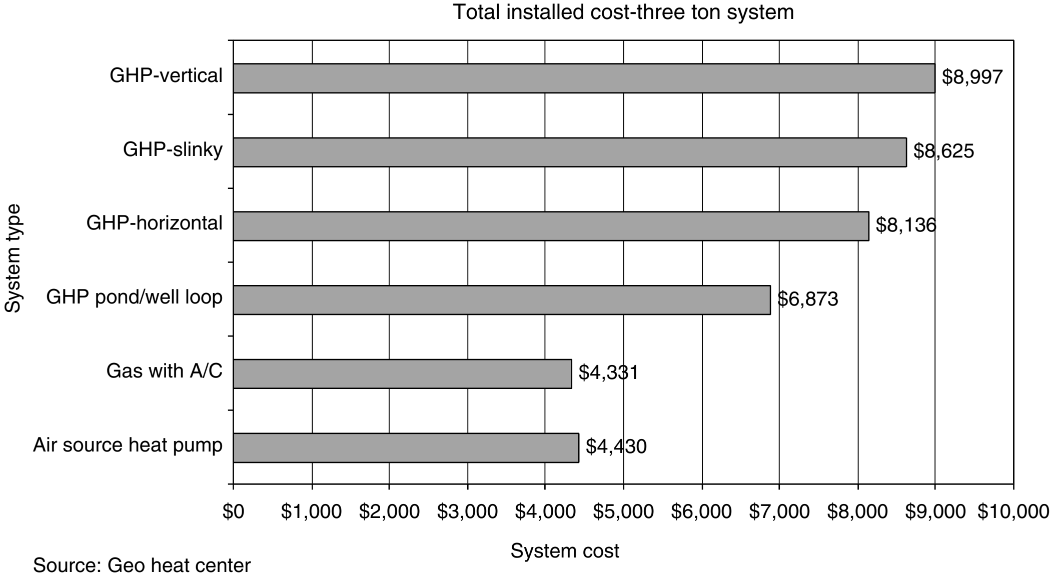
Even though geothermal heat pumps have been around for decades, this still remains a niche market. This technology still faces numerous challenges including reducing first costs, raising awareness, and developing a sustainable infrastructure.

Geothermal heat pumps take advantage of the natural constant temperature of the Earth. Just three to five feet below ground, the temperature remains between 50 and 60°F (10°C–16°C) year round. The ground temperature is warmer than the air above it in the winter and cooler than the air in the summer. Geothermal heat pumps take advantage of this difference to heat and cool buildings [6,7].



Source: Geo heat center

FIGURE 9.8 Average Loop Costs by GHP System Size.



Source: Geo heat center

FIGURE 9.9 Total Installed Cost for Three Ton GHP Systems by Type.

The heat pump must compensate for the differences between where the heat is absorbed (e.g., the source) and the temperature where the heat is delivered (e.g., the "sink." This difference is called the "lift" and the larger the "lift," the more power is required from the heat pump. An air-source heat pump removes heat from cold outside air in the winter and delivers heat to hot outside air in the summer. The geothermal heat pump, on the other hand, recovers heat from relatively warm soil (or groundwater) in the winter and delivers heat to the same relatively cool soil (or groundwater) in the summer. As a result, the geothermal heat pump is pumping the heat over a smaller temperature difference than the air-source heat pump. This leads to higher efficiency and lower energy use [7].

The geothermal heat pump system has three major parts: the ground heat exchanger, the heat pump unit, and the air delivery system (ductwork). The heat exchanger is a system of pipes called a loop, which is buried in the shallow ground near the building. A fluid (usually water or a mixture of water and antifreeze) circulates through the pipes to absorb or deposit heat within the ground.

In the winter, the heat pump removes heat from the heat exchanger and transfers it into the indoor air delivery system. In the summer, the process is reversed, and the heat pump moves heat from the indoor air into the heat exchanger. The heat removed from the indoor air during the summer can also be used to heat water.

In most standard installations, especially in the residential market, the geothermal heat pump consists of a single package water-to-air heat pump. All components are contained in a single enclosure that is about the same size as a small gas furnace. The unit includes a refrigerant-to-water heat exchanger, refrigerant piping and control valve, compressor, air coil (heats in winter; cools and dehumidifies in summer), fan and controls. Nearly all geothermal heat pump units use refrigerant R-22.

Manufacturers also offer split systems, water-to-water heat pumps, multispeed compressors, dual compressor, and rooftop versions of this equipment to suit various applications [8].

9.3.1 The Loop

The ground connection, or loop, provides the means of transferring heat to the earth in summer, and extracting heat from the earth in winter. Physically, the "ground loop" consists of several lengths of plastic pipe typically installed either in horizontal trenches or vertical holes that are covered up with earth.

Fluid inside the ground loop, either water or refrigerant, is pumped through a heat exchanger in the geothermal heat pump. In the summer, it absorbs heat from the refrigerant hot zone and carries it to the ground through the ground loop piping. In winter, it absorbs heat from the earth through the ground loop, and then transfers that heat to the refrigerant cold zone.

The length of the ground loop is determined by the heating and cooling loads, which are determined in turn by the home or building, its design and construction, orientation, and climate.

Once installed, the loop remains out of sight beneath the surface. The ground loop consists of polyethylene piping which is the same kind used for cross-country natural gas lines. It will not degrade, corrode, or break down in ground or water contact, so proper installations are projected to last at least 50 years [9].

Sometimes geothermal heat pumps are installed using a variation on this practice called direct exchange (DX). This method uses copper piping placed underground and as the refrigerant is pumped through the loop, the heat is transferred directly through the copper to the earth.

The loop field should be designed and installed by professionals who follow the guidelines established by the International Ground Source Heat Pump Association (IGSHPA). Installers should be certified by IGSHPA or demonstrate equivalent training by manufacturers or other recognized authorities.

Most loops are installed either horizontally or vertically in the ground, or submersed in water in a pond or lake. In most cases, the fluid runs through the loop in a closed system, but open-loop systems may be used where local codes permit. Each type of loop configuration has advantages and disadvantages.

Horizontal Ground Closed Loops. This configuration is the most cost-effective when adequate land available and trenches are easy to dig. Workers use trenchers or backhoes to dig the trenches three to six feet below the ground and then lay a series of parallel plastic pipes. They backfill the trench, taking care not to allow sharp rocks or debris to damage the pipes. A typical horizontal loop will be 400 to 600 ft. long per ton of heating and cooling capacity.

Vertical Ground Closed Loops. This type of loop configuration is used under the following conditions:

- There is insufficient land to permit horizontal buildings with large heating and cooling loads,
- The earth is rocky close to the surface, or
- In retrofit applications where minimum disruption of the landscaping is desired.

Contractors bore vertical holes in the ground 150 to 450 ft. deep. Each hole contains a single loop of pipe with a U-bend at the bottom. After the pipe is inserted, the hole is backfilled or grouted. Each vertical pipe is then connected to a horizontal pipe, which is also concealed underground. The horizontal pipe then carries fluid in a closed system to and from the geothermal heat pump system.

Vertical loops are generally more expensive to install, but require less piping than horizontal loops because the earth deeper down is cooler in summer and warmer in winter [9].

The major advantage of the vertical design is that it places the loop in a much more thermally stable zone. Soil at 100 ft. is not subject to the same temperature fluctuations as soil at a 4 or 5 ft. depth. Vertical loop configurations are most appropriate in extreme climate zones.

Open Loop Systems. Open loops may be cost-effective if ground water is plentiful. They are the simplest to install and have been used successfully for decades in areas where local codes permit. In this type of system, ground water from an aquifer is piped directly from the well to the building, where it transfers its heat to a heat pump. After it leaves the building, the water is pumped back into the same aquifer via a second well-called a discharge well-located at a suitable distance from the first.

This configuration requires a slightly larger well pump is installed to provide for the water required by the heat pump. A major concern is water disposal. Open loops have used ponds, lakes, rivers, irrigation ditches, and return (or injection) wells. It is also important to maintain the water quality. Since the water either absorbs or gives up heat, but is not altered in any other way, it leaves the geothermal heat pump unit as pure as it was when it entered it.

Pond Closed Loops. If the building is near a body of surface water, such as a pond or lake, this type of loop design may be the most economical. The fluid circulates through polyethylene piping in a closed system. Typically, workers run the pipe to the water and then submerge long sections under water. The pipe may be coiled in a slinky shape to fit more of it into a given amount of space. Geothermal heat pump experts recommend using a pond loop only if the water level never drops below six to eight feet at its lowest level to assure sufficient heat-transfer capability. Pond loops used in a closed system have no adverse impacts on the aquatic system.

Standing Column Well System. Standing column wells have been used in installations in the northeast United States. Standing wells are typically six inches in diameter and may be as deep as 1,500 ft.. Temperate water from the bottom of the well is withdrawn, circulated through the heat pump's heat exchanger, and returned to the top of the water column in the same well.

A standing well requires plentiful ground water. In normal circumstances, the water diverted for building (potable) use is replaced by constant-temperature ground water, which makes the system act like a true open-loop system [9].

9.3.2 Costs

When comparing heating systems, safety, installation cost, operating costs, and maintenance costs must be considered. The table below compares the various types of central heating systems using the lifecycle cost analysis Table 9.1.

A study by the Environmental Protection Agency compared six locations representing major climate zones in the U.S. The cities (Burlington, VT; Chicago, IL; upper New York City; Portland, OR; Atlanta, GA; and Phoenix, AZ) were chosen to compare the [10,11] performance and costs of emerging high-efficiency space-conditioning equipment with equipment already on the market.

In all locations, geothermal heat pumps were the most efficient heating and cooling systems over other types of space-conditioning equipment including high-efficiency gas furnaces and air conditioners. Geothermal heat pump installations in both new and existing homes may reduce energy consumption 25 to 75 percent compared to older or conventional replacement systems. Geothermal heat pumps also had the lowest annual operating costs.

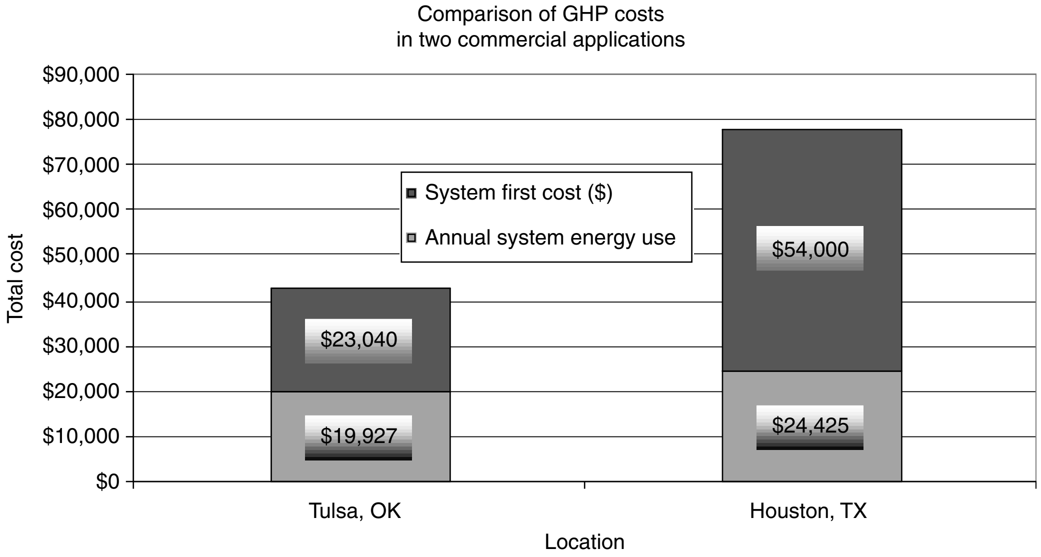
Geothermal heat pumps have also been installed in hundreds of commercial and institutional buildings throughout the United States. Some of the largest installations include 24,000 square foot administration building at Fort Polk, LA in 1993 and an 80,000 square foot office building in Allentown, PA as well as numerous schools throughout the United States.

The Fort Polk Project illustrates the diversity of applications in which geothermal heat pumps have been used in commercial settings. This $18 million project, completed in 1996, was projected to reduce annual maintenance and energy costs by more than $3 million annually—a projected $44 million savings over the life of the project. The 300 mile facility houses 23,000 military personnel and also includes a military hospital, administration buildings, training centers, and storage facilities.

The geothermal installations included replacing more than 3,000 air source heat pumps with geothermal heat pumps. This replacement effectively raised the installed SEER levels from 7 to 15.5, a significant energy savings and performance improvement. The total installation involved vertical drilling of more than 1.8 million ft., or approximately 686 square miles. This project is the largest geothermal heat pump installation in the world and involved more than nine separate drilling contractors [12].

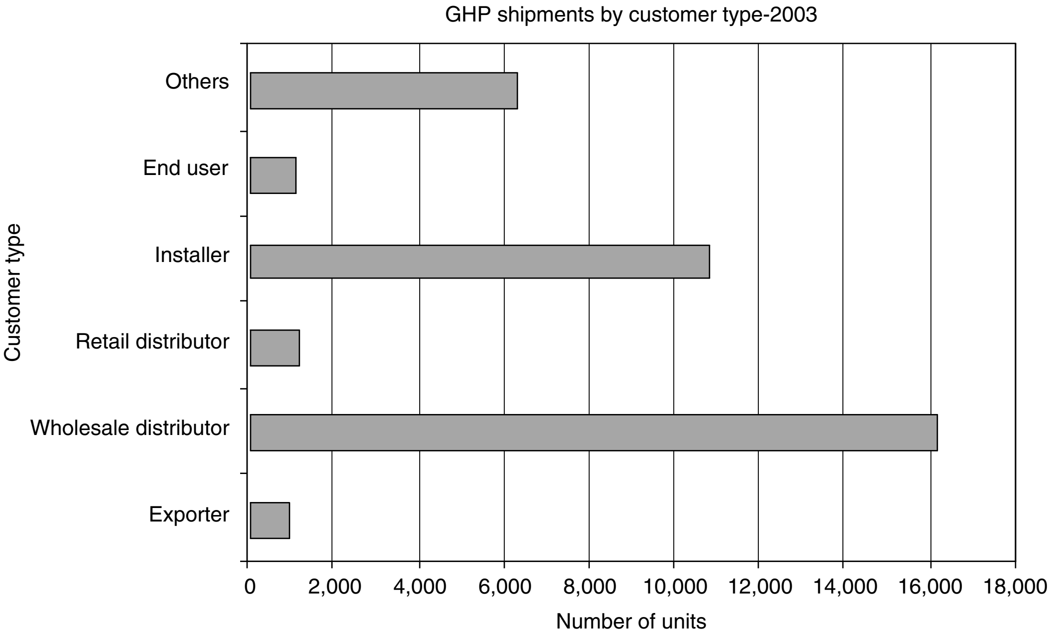
TABLE 9.1 Comparison of Costs for Residential Heating Systems

Compare	Safety	Installation Cost	Operating Cost	Maintenance Cost	Life-Cycle Cost
Combustion-based	A Concern	Moderate	Moderate	High	Moderate
Heat pump	Excellent	Moderate	Moderate	Moderate	Moderate
Geothermal Heat Pump	Excellent	High	Low	Low	Low



Source: Analysis by S.P. Kavanaugh (1998), for the U.S. Department of Energy-Oak Ridge National Laboratory, December 2001

FIGURE 9.10 Comparison of Commercial GHP Installation Costs by Location.



Source: Energy information administration, from EIA-902 "Annual geothermal heat pump manufacturers survey."

FIGURE 9.11 GHP Shipments by Customer Type in 2003.

An evaluation of a 4000-home comprehensive GHP retrofit at the U.S. Army's Fort Polk in Louisiana showed that the GHPs reduced summer peak electric demand on military base by 7.5 MW, or 43 percent, and reduced electricity consumption in post housing by 33 percent, while eliminating natural gas consumption completely [13].

Figure 9.10 illustrates the average installed costs for two geothermal heat pump installations in two locations. It also demonstrates that the total installation costs will vary based upon a number of factors, including climate, soil type, and drilling costs.

Installation Trends. The Energy Information Administration (EIA) conducts an annual survey of geothermal heat pump shipments on a per ton basis. The next two figures illustrate the most recent data collected regarding GHPS. The total ton capacity of geothermal heat pumps peaked in 1999 but it has been declining steadily ever since.

Figure 9.11 illustrates that the dominant customer group receiving geothermal heat pump shipments are the key trade allies of the wholesale distributors and installers.

9.4 Conclusions

According to the most recent government estimates, there are more than 900,000 geothermal heat pump installations in the United States. These installations have led to significant energy savings and reductions in carbon emissions:

- Elimination of more than 5.2 million metric tons of CO2 annually
- Elimination of more than 1.4 million metric tons of carbon equivalent annually
- Annual savings of more than 7 billion kWh!
- Annual savings of more than 36 trillion Btus of fossil fuels
- Reduced electricity demand of 2.3 million kW

The following organizations are able to provide more detailed information about both the costs and benefits of purchasing and installing a geothermal heat pump system:

- DOE Geothermal Technologies Program (www.eere.energy.gov/geothermal)
- Geo-Heat Center (www.geoheat.oit)
- Geothermal Heat Pump Consortium (www.geoexchange.org)
- International Ground Source Heat Pump Association (IGHSHPA) (www.ighspa.okstate.edu)

Definition of Terms and Abbreviations

ACCA: Air Conditioning Contractors Association, a trade association that is working closely with several geothermal organizations to educate HVAC installers about geothermal heat pumps.

ARI: Air-conditioning and Refrigeration Institute

ASHRAE: American Society of Heating, Refrigeration, and Air Conditioning Engineers

COP: Coefficient of Performance—a measure of energy usage and efficiency used in heating and air conditioning equipment.

GHPC: Geothermal Heat Pump Consortium

GHPS: Geothermal heat pumps, also known as: ground source heat pumps, earth source/earth coupled heat pumps, geothermal heating and cooling systems, direct exchange. or "geo"among others.

HVAC: Heating, ventilation and air conditioning

IGSHPA: International Ground Source Heat Pump Association

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10

Industrial Energy Efficiency and Energy Management

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10.1 Introduction

The industrial sector in the United States is highly diverse—consisting of manufacturing, mining, agriculture and construction activities—and consumes one-third of the nation's primary energy use, at an annual cost of around \$100 billion.[1] The industrial sector encompasses more than 3 million

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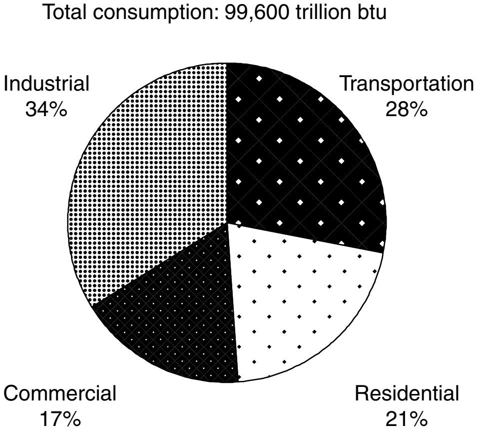

FIGURE 10.1 U.S. energy use by sector, 2004. (From U.S. DOE Energy Information Agency, *Industrial Sector Energy Price and Expenditure Estimates for 2001*, U.S. Department of Energy, Office of Industrial Technologies, Industrial Technology Program, Washington, DC, 2005.)

establishments engaged in manufacturing, agriculture, forestry, construction, and mining. These industries require energy to light, heat, cool, and ventilate facilities (end uses characterized as energy needed for comfort). They also use energy to harvest crops, process livestock, drill and extract minerals, power various manufacturing processes, move equipment and material, raise steam, and generate electricity. Some industries require additional energy fuels for use as raw materials—or feedstocks—in their production processes. Many industries use by-product fuels to satisfy part or most of their energy requirements. In the more energy-intensive manufacturing and nonmanufacturing industries, energy used by processes dwarfs the energy demand for comfort.

U.S. sector energy use for 2004 is shown in Figure 10.1, industrial energy use is shown in Figure 10.2, and industrial electricity use is shown in Figure 10.3.

Manufacturing companies, which use mechanical or chemical processes to transform materials or substances to new products, account for about 80% of the total industrial sector use. The “big three” in energy use are petroleum, chemicals, and primary metals; these manufacturers together consume over one-half of all industrial energy. The “big six,” which adds the pulp and paper group, the food and kindred products group, as well as the stone, clay and glass group, together account for 88% of manufacturing energy use, and over 70% of all industrial sector energy consumption.[2]

According to the U.S. Energy Information Administration, energy efficiency in the manufacturing sector improved by 25% over the period 1980–1985.[3] During that time, manufacturing energy use declined 19%, and output increased 8%. These changes resulted in an overall improvement in energy efficiency of 25%. However, the “big five” did not match this overall improvement; although their energy use declined 2%, their output decreased by 5%, resulting in only a 17% improvement in energy efficiency during 1980–1985. This five-year record of improvement in energy efficiency of the manufacturing sector

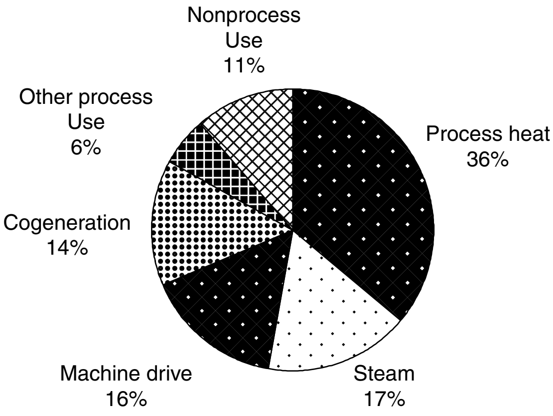

FIGURE 10.2 Manufacturing energy use 1998 (end use basis). (From U.S. Department of Energy EIA MECS, 2002.)

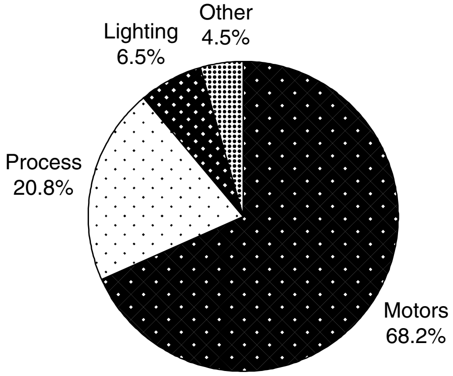

FIGURE 10.3 Manufacturing electrical energy use 1998 (end use basis). (From Manufacturer Energy Consumption Survey, 1998; U.S. Depatment of Energy; Energy Information Agency, 2002.)

came to an end, with total energy use in the sector growing by 10% from 1986 to 1988, and overall manufacturing energy intensity stagnated during 1985–1994 due to falling and low energy prices, economic recession during part of this period, and a recovery in some of the more energy-intensive groups such as steel and aluminum production. However, industrial energy intensity again declined significantly during the late 1990s due to high capital investment, rapid industrial modernization, and explosive growth of "high-tech" industries that are not energy-intensive.

Since 1980, the overall value of industrial output has increased through 2003, while the total energy consumed by the industrial sector has fallen overall throughout 2003.[4] This relationship is shown in Figure 10.4, where the consumption index for both primary and site energy is greater than the output index before 1980, and less afterward, with the gap consistently widening in the late 1980s. New energy-efficient technology and the changing production mix from the manufacture of energy-intensive products to less intensive products are responsible for this change.

Continuing this overall record of energy-efficiency improvements in industry will require emphasis on energy-management activities, as well as making capital investments in new plant processes and facilities improvements. Reducing the energy costs per unit of manufactured product is one way that the United States can become more competitive in the global industrial market. The U.S. Department of Energy has

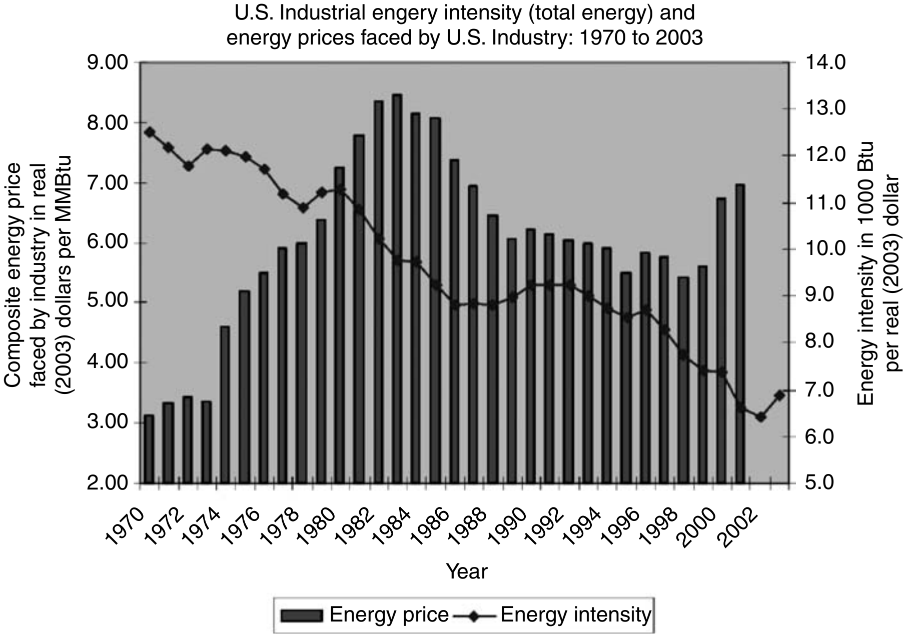

FIGURE 10.4 Industrial energy intensity 1980–2003. (From National Association of Manufacturers, 2005. With permission.)

formally recognized these multiple benefits to the country by including the following statement in its 2004 Industrial Technology Program Report: "By developing and adopting more energy-efficiency technologies, U.S. industry can boost its productivity and competitiveness while strengthening national energy security, improving the environment, and reducing emissions linked to global climate change."[5] Additionally, it is interesting to note that Japan—one of the U.S.' major industrial competitors—has a law that says every industrial plant must have a full-time energy manager.[6]

Several studies of industrial energy efficiency have been performed in the last few years, and the results from the studies have been fairly consistent—that there is a readily achievable, cost-effective, 20% reduction in industrial consumption using good energy management practices and energy-efficient equipment. The most recent, highly credible study that has been done of the potential for industrial energy-efficiency improvement in the U.S. is the "Energy Use, Loss and Opportunities Analysis: U.S. Manufacturing and Mining" report issued by the U.S. Department of Energy, Office of Industrial Technologies, in December 2004.[1] This report, together with the together with the report on "Efficiency and innovation in U.S. Manufacturing Energy Use" from the National Association of Manufacturers (NAM), conducted with the Alliance to Save Energy, make a strong and very credible case for the achievement of a 20% savings in energy for the industrial sector.[4]

Earlier studies by the national laboratories in the U.S. produced a composite report, "Scenarios for a Clean Energy Future," in 2000 that also supported the achievement of a 20% reduction in industrial energy use. One element of this study was to examine data from the Industrial Assessment Center Program (discussed in more detail later in this chapter), from 12,000 plant energy audits making 82,000 recommendations for actions to increase energy efficiency in the facilities audited.[7] Results from these real-world energy audits also supported the 20% reduction estimate.

Other groups, such as Lawrence Berkeley Laboratory, have performed studies of industrial energy efficiency, and their results from their studies show improvements of 20% or greater in industrial energy efficiency.[8] A recent study from the American Council for an Energy Efficient Economy (ACEEE) showed the potential for a 40% reduction in electricity use for fan and pumping applications in industry.[9] Specific details and recommendations from these studies are presented in Section 10.5.

10.2 Industrial Energy Management and Efficiency Improvement

10.2.1 Setting Up an Energy-Management Program

The effectiveness of energy utilization varies with specific industrial operations because of the diversity of the products and the processes required to manufacture them. The organization of personnel and operations, involved also varies. Consequently, an effective energy management program should be tailored for each company and its plant operations. There are some generalized guidelines, however, for initiating and implementing an energy management program. Many large companies have already instituted energy management programs and have realized substantial savings in fuel and electric costs. Smaller industries and plants, however, often lack the technical personnel and equipment to institute and carry out effective programs. In these situations, reliance on external consultants may be appropriate to initiate the program. Internal participation, however, is essential for success. A well-planned, organized, and executed energy management program requires a strong commitment by top management.

Assistance also can be obtained from local utilities. Utility participation would include help in getting the customer started on an energy management program, technical guidance, or making information available. Most electric and gas utilities today have active programs that include training of customer personnel or provision of technical assistance. Table 10.1 summarizes the elements of an effective energy management program. These will now be discussed in more detail.

TABLE 10.1 Elements of an Energy Management Program

	Phase 1: Management Commitment
1.1	Commitment by management to an energy management program
1.2	Assignment of an energy management coordinator
1.3	Creation of an energy management committee of major plant and department representatives
	Phase 2: Audit and Analysis
2.1	Review of historical patterns of fuel and energy use
2.2	Facility walk-through survey
2.3	Preliminary analyses, review of drawings, data sheets, equipment specifications
2.4	Development of energy audit plans
2.5	Conduct facility energy audit, covering a. Processes b. Facilities and equipment
2.6	Calculation of annual energy use based on audit results
2.7	Comparison with historical records
2.8	Analysis and simulation step (engineering calculations, heat and mass balances, theoretical efficiency calculations, computer analysis and simulation) to evaluate energy management options
2.9	Economic analysis of selected energy management options (life cycle costs, rate of return, benefit–cost ratio)
	Phase 3: Implementation
3.1	Establish energy effectiveness goals for the organization and individual plants
3.2	Determine capital investment requirements and priorities
3.3	Establish measurement and reporting procedures, install monitoring and recording instruments and submeters as required.
3.4	Institute routine reporting procedures ("energy-tracking" charts) for managers and publicize results
3.5	Promote continuing awareness and involvement of personnel
3.6	Provide for periodic review and evaluation of overall energy management program

10.2.1.1 Phase I: Management Commitment

A commitment by the directors of a company to initiate and support a program is essential. An energy coordinator is designated and an energy management committee is formed. The committee should include personnel representing major company activities utilizing energy. A plan is formulated to set up the programs with a commitment of funds and personnel. Realistic overall goals and guidelines in energy savings should be established based on overall information in the company records, projected activities, and future fuel costs and supply. A formal organization as described earlier is not an absolute requirement for the program; smaller companies will simply give the energy management coordination task to a staff member.

Organizing for Energy Conservation Programs. The most important organizational step which will effect the success of an energy management (e.m.) program is the appointment of one person who has full responsibility for its operation. Preferably that person should report directly to the top management position and be given substantial authority in directing technical and financial resources within the bounds set by the level of management commitment. It is difficult to stress enough the importance of making the position of plant energy manager a full-time job. Any diversion of interest and attention to other aspects of the business is bound to badly affect the e.m. program. One reason is that the greatest opportunity for energy cost control and energy-efficiency gains is in improved operational and maintenance practices. Implementing and sustaining good operational and maintenance procedures is an exceedingly demanding job and requires a constant attention and a dedication to detail that is rarely found in corporate business life. The energy manager should be energetic, enthusiastic, dedicated, and political.

The second step is the appointment of the plant e.m. committee. This should consist of one group of persons who are able to and have some motivation for cutting fuel and electric costs and a second group who have the technical knowledge or access to data needed for the program department managers or their assistants. Thus, the e.m. committees should include labor representatives, the maintenance department head, a manager of finance or data storage, some engineers, and a public relations person. The energy manager should keep up to date on the energy situation daily, convene the committee weekly, and present a definitive report to top management at least monthly and at other times when required by circumstance. It is suggested also that several subcommittees be broken out of the main committee to consider such important aspects as capital investments, employee education, operator-training programs, external public relations, and so on. The committee will define strategy, provide criticism, publish newsletters and press releases, carry out employee programs, argue for the acceptance of feasible measures before management, represent the program in the larger community, and be as supportive as possible to the energy coordinator. This group has the most to risk and the most to gain. They must defend their own individual interests against the group but at the same time must cooperate in making the program successful and thus be eligible for rewards from top management for their good work and corporate success.

As the e.m. program progresses to the energy audit and beyond, it will be necessary to keep all employees informed as to its purposes, its goals, and how its operation will impact plant operations and employee routine, comfort, and job performance. The education should proceed through written and oral channels as best benefits the organizational structure. Newsletters, posters, and employee meetings have been used successfully.

In addition to general education about energy conservation, it may prove worthwhile to offer specialized courses for boiler, mechanical and electrical equipment operators and other workers whose jobs can affect energy utilization in the plant. The syllabuses should be based on thermodynamic principles applied to the systems involved and given on an academic level consistent with the workers backgrounds. Long-range attempts to upgrade job qualifications through such training can have very beneficial effects on performance. The courses can be given by community colleges, by private enterprises, professional societies or by in-house technical staff, if available.

The material presented here on organization is based on the presumption that a considerable management organization already exists and that sufficient technical and financial resources exist for support of the energy management program as outlined. Obviously, very small businesses cannot operate on this scale, however, we have found many small companies that have carried out effective energy management efforts.

Setting Energy Conservation Goals. It is entirely appropriate and perhaps even necessary to select an energy reduction goal for the first year of the program very early in the program. The purpose is to gain the advantage of the competitive spirit of those employees that can be aroused by a target goal. Unfortunately, the true potential for conservation and the investment costs required to achieve it are not known until the plant energy audit is completed and a detailed study made of the data. Furthermore, a wide variety of energy-use patterns exists even with a single industry.

However, looking at the experience of other industries that have set goals and met them can provide some useful guidance.

An excellent example of a long-term successful energy management program in a large industrial corporation is that of the 3M Company, headquartered in St. Paul, Minnesota.[10] 3M is a large, diversified manufacturing company with more than 50 major product lines; it makes some 50,000 products at over 50 different factory locations around the country. The corporate energy management objective is to use energy as efficiently as possible in all operations; the management believes that all companies have an obligation to conserve energy and all other natural resources.

Energy productivity at 3M improved 63% from 1973 to 2004. They saved over $70 million in 2004 because of their energy management programs, and saved a total of over $1.5 billion in energy expenses from 1973 to 2004. From 1998 through 2004, they reduced their overall energy use by 27% in their worldwide operations.[11] Their program is staffed by three to six people who educate and motivate all levels of personnel on the benefits of energy management. The categories of programs implemented by 3M include conservation, maintenance procedures, utility operation optimization, efficient new designs, retrofits through energy surveys, and process changes.

Energy-efficiency goals at 3M are set and then the results are measured against a set standard to determine the success of the programs. The technologies that have resulted in the most dramatic improvement in energy efficiency include heat-recovery systems, high-efficiency motors, variable-speed drives, computerized facility management systems, steam-trap maintenance, combustion improvements, variable-air-volume systems, thermal insulation, cogeneration, waste-steam utilization, and process improvements. Integrated manufacturing techniques, better equipment utilization, and shifting to nonhazardous solvents have also resulted in major process improvements.

The energy management program at 3M has worked very well, but the company's management is not yet satisfied. They have set a goal of further improving energy efficiency at a rate of 2%–3% per year for the next 5 years. This goal will produce a 10%–15% reduction in energy use per pound of product or per square foot of building space. They expect to substantially reduce their emissions of waste gases and liquids, to increase the energy recovered from wastes, and to constantly increase the profitability of their operations. 3M continues to stress the extreme importance that efficient use of energy can have on their industrial productivity.

10.2.1.2 Phase 2: Audit and Analysis

Energy Audit of Equipment and Facilities. Historical data for the facility should be collected, reviewed, and analyzed. The review should identify gross energy uses by fuel types, cyclic trends, fiscal year effects, dependence on sales or work load, and minimum energy-use ratios. Historical data are graphed in a form similar to the one shown in Chapter 5. Historical data assist in planning a detailed energy audit and alert the auditors as to the type of fuel and general equipment to expect. A brief facility walk-through is recommended to establish the plant layout, major energy uses, and primary processes or functions of the facility.

The energy audit is best performed by an experienced or at least trained team, since visual observation is the principal means of information gathering and operational assessment. A team would have from three to five members, each with a specific assignment for the audit. For example, one auditor would check the lighting, another the HVAC system, another the equipment and processes, another the building structure (floor space, volume, insulation, age, etc.), and another the occupancy use schedule, administration procedures, and employees' general awareness of energy management.

The objectives of the audit are to determine how, where, when, and how much energy is used in the facility. In addition, the audit helps to identify opportunities to improve the energy-use efficiency and its operations. Some of the problems encountered during energy audits are determining the rated power of equipment, determining the effective hours of use per year, and determining the effect of seasonal, climatic, or other variable conditions on energy use. Equipment ratings are often obscured by dust or grease (unreadable nameplates). Complex machinery may not have a single nameplate listing the total capacity, but several giving ratings for component equipment. The effect of load is also important because energy use in a machine operating at less than full load may be reduced along with a possible loss in operating efficiency.

The quantitative assessment of fuel and energy use is best determined by actual measurements under typical operational conditions using portable or installed meters and sensing devices. Such devices include light meters, ammeters, thermometers, airflow meters, recorders, and so on. In some situations, sophisticated techniques such as infrared scanning or thermography are useful. The degree of measurement and recording sophistication naturally depends on available funds and the potential savings anticipated. For most situations, however, nameplate and catalog information are sufficient to estimate power demand. Useful information can be obtained from operating personnel and their supervisors—particularly as it relates to usage patterns throughout the day. A sample form that can be used for recording audit data is shown in Chapter 5 (Figure 5.3).

The first two columns of the form are self-explanatory. The third column is used for the rated capacity of the device, (e.g., 5kW). The sixth column is used if the device is operated at partial load. Usage hours (column 7) are based on all work shifts, and are corrected to account for the actual operating time of the equipment. The last three columns are used to convert energy units to a common basis (e.g., MJ or Btu).

Data recorded in the field are reduced easily by the use of specialized software or spread sheets that provide uniform results and summaries in a form suitable for review or for further analysis. Computer analysis also provides easy modification of the results to reflect specific management reporting requirements or to present desired comparisons for different energy use, types of equipment, and so on.

In-Plant Metering. Submetering reduces the work and time required for an energy audit; indeed, it does much more that that. Because meters are tools for assessing production control and for measuring equipment efficiency, they can contribute directly to energy conservation and cost containment. Furthermore submetering offers the most effective way of evaluating the worth of an energy-efficiency measure. Too many managers accept a vendor's estimate of fuel savings after buying a recuperator. They may scan the fuel bills for a month or two after the purchase to get an indication of savings—usually in vain—and then relax and accept the promised benefit without ever having any real indication that it exists. It may well be that, in fact, it does not yet exist. The equipment without directly metering the fuel input. It is estimated that at least 2.5% waste is recoverable by in-plant metering.

Oil meters are just as effective as gas meters used in the same way and are even less expensive on an energy-flow basis. Electric meters are particularly helpful in monitoring the continued use of machines or lighting during shutdown periods and for evaluating the efficacy of lubricants and the machineability of feed stock. The use of in-plant metering can have its dark side too. The depressing part is the requirement for making periodic readings. It does not stop even there. Someone must analyze the readings so that something can be done about them. If full use is to be made of the information contained in meter readings, it must be incorporated into the energy information portion of the management information system. At the very least each subreading must be examined chronologically to detect malfunctions or losses of efficiency. Better still, a derived quantity such as average energy per unit of production should be examined.

A Special Case: Energy Audit of a Process. In some manufacturing and process industries it is of interest to determine the energy content of a product. This can be done by a variation of the energy audit techniques described earlier. Since this approach resembles classical financial accounting, it is sometimes called energy accounting. In this procedure the energy content of the raw materials is determined in a consistent set of energy units. Then, the energy required for conversion to a product is accounted for in the same units. The same is done for energy in the waste streams and the by-products. Finally, the net energy content per unit produced is used as a basis for establishing efficiency goals.

In this approach, all materials used in the product or used to produce it are determined. Input raw materials used in any specific period are normally available from plant records. Approximations of specific energy content for some materials can be found in the literature or can be obtained from the U.S. Department of Commerce or other sources. The energy content of a material includes that due to extraction and refinement as well as an inherent heating value it would have as a fuel prior to processing. Consequently, nonfuel-type ores in the ground are assigned zero energy and petroleum products are assigned their alternate value as a fuel prior to processing in addition to the refinement energy. The energy of an input metal stock would include the energy due to extraction, ore refinement to metal, and any milling operations.

Conversion energy is an important aspect of the energy audit, since it is under direct control of plant management. All utilities and fuels coming into the plant are accounted for. They are converted to consistent energy units (joules or Btu) using the actual data available on the fuels or using approximate conversions.

Electrical energy is assigned the actual fuel energy required to produce the electricity. This accounts for power conversion efficiencies. A suggested approach is to assume (unless actual values are available from your utility) that 10.8 MJ (10,200 Btu) is used to produce 3.6 MJe (1 kWh), giving a fuel conversion efficiency of $3.6 \div 10.8 = 0.33$ or 33%.

The energy content of process steam includes the total fuel and electrical energy required to operate the boiler as well as line and other losses. Some complexities are introduced when a plant produces both power and steam, since it is necessary to allocate the fuel used to the steam and power produced. One suggested way to make this allocation is to assume that there is a large efficient boiler feeding steam to a totally condensing vacuum turbine. Then, one must determine the amount of extra boiler fuel that would be required to permit the extraction of steam at whatever pressure while maintaining the constant load on the generator. The extra fuel is considered the energy content of the steam being extracted.

Waste disposal energy is that energy required to dispose of or treat the waste products. This includes all the energy required to bring the waste to a satisfactory disposal state. In a case where waste is handled by a contractor or some other utility service, it would include the cost of transportation and treatment energy.

If the plant has by-products or coproducts, then energy credit is allocated to them. A number of criteria can be used. If the by-product must be treated to be utilized or recycled (such as scrap), then the credit would be based on the raw material less the energy expended to treat the by-product for recycle. If the by-product is to be sold, the relative value ratio of the by-product to the primary product can be used to allocate the energy.

Analysis of Audit Results, Identification of Energy Management Opportunities. Often the energy audit will identify immediate energy management opportunities, such as unoccupied areas that have been inadvertently illuminated 24 hours per day, equipment operating needlessly, and so on. Corrective housekeeping and maintenance action can be instituted to achieve short-term savings with little or no capital investment.

An analysis of the audit data is required for a more critical investigation of fuel waste and identification of the potential for conservation. This includes a detailed energy balance of each process, activity, or facility. Process modification and alternatives in equipment design should be formulated, based on technical feasibility and economic and environmental impact. Economic studies to determine payback, return on investment, and net savings are essential before making capital investments.

10.2.1.3 Phase 3: Implementation and Submeters

At this point goals for saving energy can be established more firmly and priorities set on the modification and alterations to equipment and the process: Effective measurement and monitoring Procedures are essential in evaluating progress in the energy management program. Routine reporting procedures between management and operations should be established to accumulate information on plant performance and to inform plant supervisiors of the effectiveness of their operation. Time-tracking charts of energy use and costs can be helpful involving employees and recognizing their contributions facilitate the achievement of objectives. Finally, the program must be continually reviewed and analyzed with regard to established goals and procedures.

10.2.2 The Energy Audit Report

Energy audits do not save money and energy for companies unless the recommendations are implemented. Audit reports should be designed to encourage implementation. The goal in writing an audit report should not be the report itself; rather, it should be to achieve implementation of the report recommendations and thus achieve increased energy efficiency and energy cost savings for the customer. In this section, the authors discuss their experience with writing industrial energy audit reports and suggest some ways to make the reports more successful in terms of achieving a high rate of the recommendations.[12]

- Present information visually. The authors present their client's energy-use data visually with graphs showing the annual energy and demand usage by month. These graphs give a picture of use patterns. Any discrepancies in use show up clearly.

- Make calculation sections helpful. The methodology and calculations used to develop specific energy management opportunity recommendations are useful in an audit report. Including the methodology and calculations gives technical personnel the ability to check the accuracy of one's assumptions and one's work. However, not every reader wants to wade through pages describing the methodology and showing the calculations. Therefore, the authors provide this information in a technical supplement to the audit report. Because this section is clearly labeled as the technical supplement, other readers are put on notice as to the purpose of this section.
- Use commonly understood units. When preparing the report, be sure to use units that the client will understand. Discussing energy savings in terms of Btus (British thermal units) may only be meaningful to the engineers and more technical readers. For management and operating personnel, kilowatt-hours (for electricity) or therms (for natural gas) are better units, because most energy bills use these units.
- Explain your assumptions. A major problem with many reports is a failure to explain the assumptions underlying the calculations. For example, when the authors use operating hours in a calculation, it is always carefully shown how the number was figured; for example, "Your facility operates from 7:30 am to 8:00 pm, five days a week, 51 weeks per year. Therefore, we will use 3188 h in our calculations."

  When basic assumptions and calculations are shown, the reader can make adjustments if those facts change. In the example above, if the facility decided to operate 24 h/day, the reader would know where and how to make changes in operating hours, because that calculation had been clearly labeled.

  The authors use one section of their report to list the standard assumptions and calculations. Thus, explanations for each of the recommendations do not have to be repeated. Some of the standard assumptions/calculations included in this section are operating hours, average cost of electricity, demand rate, off-peak cost of electricity, and the calculation of the fraction of air-conditioning load attributable to lighting.
- Be accurate and consistent. The integrity of a report is grounded in its accuracy. This does not just mean correctness of calculations. Clearly, inaccurate calculations will destroy a report's credibility, but other problems can also undermine the value of a report. Use the same terminology so that the reader is not confused. Make sure that the same values are used throughout the report. Do not use two different load factors for the same piece of equipment in different recommendations. This, for example, could happen if one calculated the loss of energy due to leaks from a compressor in one recommendation and the energy savings due to replacing the compressor motor with a high-efficiency motor in another recommendation.
- Proofread the report carefully: Typographical and spelling errors devalue an otherwise good product. With computer spell checkers, there is very little excuse for misspelled words. Nontechnical readers are likely to notice this type of error, and they will wonder if the technical calculations are similarly flawed.

10.2.2.1 Report Sections

The authors have found that the following report format meets their clients' needs and fits the authors' definition of a user-friendly report.

Executive Summary. The audit report should start with an executive summary that basically lists the recommended energy conservation measures and shows the implementation cost and dollar savings amount. This section is intended for the readers who want to see only the bottom line. Although the executive summary can be as simple as a short table, the authors add some brief text to explain the recommendations and sometimes include other special information needed to implement the recommendations. They also copy the executive summary on colored paper so that it stands out from the rest of the report.

Energy Management Plan. Following the executive summary, some information is provided to the decision makers on how to set up an energy management program in their facility. The authors view this section as one that encourages implementation of the report, so every attempt is made to try to make it as helpful as possible.

Energy Action Plan. In this subsection, the authors describe the steps that a company should consider in order to start implementing the report's recommendations.

Energy Financing Options. The authors also include a short discussion of the ways that a company can pay for the recommendations. This section covers the traditional use of company capital, loans for small businesses, utility incentive programs, and the shared savings approach of the energy service companies.

Maintenance Recommendations. The authors do not usually make formal maintenance recommendations in the technical supplement, because the savings are not often easy to quantify. However, in this section of the report, energy savings maintenance checklists are provided for lighting, heating/ventilation/air conditioning, and boilers.

The Technical Supplement. The technical supplement is the part of the report that contains the specific information about the facility and the audit recommendations. The authors' technical supplement has two main sections: one includes the report's assumptions and general calculations and the other describes the recommendations in detail, including the calculations and methodology. The authors sometimes include a third section that describes measures that were analyzed and determined not to be cost-effective, or that have payback times beyond the client's planning horizon.

Standard Calculations and Assumptions. This section was briefly described above when the importance of explaining assumptions was discussed. Here, the reader is provided with the basis for understanding many of the authors' calculations and assumptions. Included is a short description of the facility: square footage (both air-conditioned and unconditioned areas); materials of construction; type and level of insulation; etc. If the authors are breaking the facility down into subareas, those areas are described and each area is assigned a number which is then used throughout the recommendation section.

Standard values calculated in this section include operating hours, average cost of electricity, demand rate, off-peak cost of electricity, and the calculation of the fraction of air-conditioning load attributable to lighting. When a value is calculated in this section, the variable is labeled with an identifier that remains consistent throughout the rest of the report.

Audit Recommendations. This section contains a discussion of each of the energy management opportunities the authors have determined to be cost-effective. Each energy management recommendation (or EMR) which was capsulized in the executive summary is described in-depth here.

Again, the authors try to make the EMRs user-friendly. To do this, the narrative discussion is placed at the beginning of a recommendation and the technical calculations are left for the very end. In this manner, the authors allow the readers to decide for themselves whether they want to wade through the calculations.

Each EMR starts with a table that summarizes the energy, demand and cost savings, implementation cost, and simple payback period. Then follows a short narrative section that provides some brief background information about the recommended measure and explains how it should be implemented at the facility in question. If the authors are recommending installation of more than one item (lights, motors, air-conditioning units, etc.), a table is often used to break down the savings by unit or by area.

The final section of each EMR is the calculation section. Here the authors explain the methodology that was used to arrive at the report's savings estimates. The equations are provided and it is shown how the calculations are performed so that the clients can see what has been done. If they want to change the report's assumptions, they can. If some of the data the authors have used is incorrect, they can replace it with the correct data and recalculate the results. However, by placing the calculations away from the rest of the discussion rather than intermingling it, the authors do not scare off the readers who need to know the other information.

Appendix. The authors use an appendix for lengthy data tables. For example, there is a motor efficiencies table which is used in several of the authors' EMRs. Instead of repeating it in each EMR, it is printed in the appendix. The authors also include a table showing the facility's monthly energy-use history and a table listing the major energy-using equipment. Similar to the calculation section of the EMRs, the appendix allows the authors to provide backup information with out cluttering up the main body of the report.

10.3 Improving Industrial Energy Audits

10.3.1 Preventing Overestimation of Energy Savings in Audits

A frequent criticism of energy audits is that they overestimate the savings potential available to the facility. This section addresses several problem areas which can result in overly optimistic savings projections, and suggests ways to prevent mistakes.[13] This possibility of overestimation concerns many of the people and organizations that are involved in some part of this energy audit process. It concerns utilities who do not want to pay incentives for demand-side management programs if the facilities will not realize the expected results in energy or demand savings. Overestimates also make clients unhappy when their energy bills do not decrease as much as promised. The problem multiplies when a shared savings program is undertaken by the facility and an energy service company. Here, the difference between the audit projections and the actual metered and measured savings may be so significantly different that either there are no savings for the facility, or the energy service company makes no profit.

More problems are likely with the accuracy of the energy audits for industrial and manufacturing facilities than for smaller commercial facilities or even large buildings because the equipment and operation of industrial facilities is more complex. However, many of the same problems discussed here in terms of industrial and manufacturing facilities can occur in audits of large commercial facilities and office buildings. Based on the authors' auditing experience for industrial and manufacturing facilities over the last five years, it is possible to identify a number of areas where problems are likely to occur, and a number of these are presented and discussed. In addition, the authors have developed a few methods and approaches to dealing with these potential problems, and a few ways have been found to initiate energy audit analyses that lead the authors to improved results. One of these approaches is to collect data on the energy-using equipment in an industrial or manufacturing facility and then to perform both an energy and a demand balance to help insure that reasonable estimates of energy uses—and therefore, energy savings—are available for this equipment.

In addition, unfortunately, some analysts use the average cost of electricity to calculate energy savings. This can give a false picture of the actual savings and may result in overly optimistic savings predictions. This section also discusses how to calculate the correct values from the electricity bills, and when to use these values. Finally, this section discusses several common energysavings measures that are frequently recommended by energy auditors. Some of these may not actually save as much energy or demand as expected, except in limited circumstances. Others have good energy-saving potential but must be implemented carefully to avoid increasing energy use rather than decreasing it.

10.3.2 Calculating Energy and Demand Balances

The energy and demand balances for a facility are an accounting of the energy flows and power used in the facility. These balances allow the energy analyst to track the energy and power inputs and outputs (uses) and see whether they match. A careful energy analyst should perform an energy and demand balance on a facility before developing and analyzing any energy management recommendations.[14] In this way, the analyst can determine what the largest energy users are in a facility, can find out whether all—or almost all—energy uses have been identified, and can see whether more savings have been identified than are actually achievable. Making energy-use recommendations without utilizing the energy and demand balances is similar to making budget-cutting recommendations without knowing exactly where the money is currently being spent.

When the authors perform an energy survey (audit), all of the major energy-using equipment in the facility is inventoried. Then the authors list the equipment and estimate its energy consumption and demand using the data gathered at the facility, such as nameplate ratings of the equipment and operating hours. The energy balance is developed by major equipment category, such as lighting, motors, HVAC, air compressors, etc. There is also a category called *miscellaneous* to account for loads that were not individually surveyed, such as copiers, electric typewriters, computers, and other plug loads. The authors typically allocate 10% of the actual energy use and demand to the *miscellaneous* category in the demand and energy balances. (For an office building instead of a manufacturing facility, this miscellaneous load might be 15%–20%). Then, the energy and demand for each of the other categories is calculated.

10.3.2.1 Lighting

The first major category analyzed is lighting, because this is usually the category in which the authors have the most confidence for knowing the actual demand and hours of use. Thus, they believe that the energy and demand estimates for the lighting system are the most accurate, and can then be subtracted from the total actual use to let the authors continue to build up the energy and demand balance for the facility. The authors record the types of lamps and number of lamps used in each area of the facility and ask the maintenance person to show them the replacement lamps and ballasts used. With this lamp and ballast wattage data, together with a good estimate of the hours that the lights are on in the various areas, they can construct what they believe to be a fairly accurate description of the energy and demand for the lighting system.

10.3.2.2 Air-Conditioning

There is generally no other “easy” or “accurate” category to work on, so the authors proceed to either air-conditioning or motors. In most facilities, there will be some air-conditioning, even if it is just for the offices that are usually part of the industrial or manufacturing facility. Many facilities—particularly in the hot and humid southeast—are fully air-conditioned. Electronics, printing, medical plastics and devices, and many assembly plants are common ones seen to be fully air-conditioned. Boats, metal products, wood products, and plastic pipe-manufacturing facilities are most often not air conditioned. Air-conditioning system nameplate data is usually available and readable on many units, and efficiency ratings can be found from published ARI data,[15] or from the manufacturers of the equipment. The biggest problem with air-conditioning is to get runtime data that will allow the author(s) of the report to determine the number of full-load equivalent operating hours for the air-conditioning compressors or chillers. From the authors’ experience in north and north-central Florida, about 2200–2400 h are used per year of compressor runtime for facilities that have air-conditioning that responds to outdoor temperature. Process cooling requirements are much different, and would typically have much larger numbers of full-load equivalent operating hours. With the equipment size, the efficiency data, and the full-load equivalent operating hours, it is possible to construct a description of the energy and demand for the air-conditioning system.

10.3.2.3 Motors

Turning next to motors, the authors begin looking at one of the most difficult categories to deal with in the absence of fully metered and measured load factors on each motor in the facility. In a one-day plant visit, it is usually impossible to get actual data on the load factors for more than a few motors. Even then, that data is only good for the one day that it was taken. Very few energy-auditing organizations can afford the time and effort to make long-term measurements of the load factor on each motor in an industrial or manufacturing facility. Thus, estimating motor load factors becomes a critical part of the energy and demand balance, and also a critical part of the accuracy of the actual energy audit analysis. Motor nameplate data shows the horsepower rating, the manufacturer, and sometimes the efficiency. If not, the efficiency can usually be obtained from the manufacturer, or from standard references such as the *Energy-Efficient Motor Systems Handbook*,[16] or from software databases such as MotorMaster produced by the Washington State Energy Office.[17] The authors inventory all motors over 1 hp, and sometimes try to look at the smaller ones if there is enough time.

Motor runtime is another parameter that is very difficult to obtain. When the motor is used in an application where it is constantly on is an easy case. Ventilating fans, circulating pumps, and some process-drive motors are often in this class because they run for a known, constant period of time each year. In other cases, facility operating personnel must help provide estimates of motor runtimes. With data on the horsepower, efficiency, load factor, and runtimes of motors, it is possible to construct a detailed table of motor energy and demands to use in the report's balances. Motor load factors will be discussed further in a later section of this paper.

10.3.2.4 Air Compressors

Air compressors are a special case of motor use with most of the same problems. Some help is available in this category because some air compressors have instruments showing the load factor, and some have runtime indicators for hours of use. Most industrial and manufacturing facilities will have several air compressors, and this may lead to some questions as to which air compressors are actually used and how many hours they are used. If the air compressors at a facility are priority-scheduled, it may turn out that one or more of the compressors are operated continuously, and one or two smaller compressors are cycled or unloaded to modulate the need for compressed air. In this case, the load factors on the larger compressors may be unity. Using this data on the horsepower, efficiency, load factor, and runtimes of the compressors, the authors develop a detailed table of compressor energy use and demand for the report's energy and demand balances.

10.3.2.5 Other Process Equipment

Specialized process equipment must be analyzed on an individual basis because it will vary tremendously depending on the type of industry or manufacturing facility involved. Much of this equipment will utilize electric motors and will be covered in the motor category. Other electrically-powered equipment, such as drying ovens, cooking ovens, welders, and laser and plasma cutters, are nonmotor electric uses and must be treated separately. Equipment nameplate ratings and hours of use are necessary to compute the energy and demand for these items. Process chillers are another special class that are somewhat different from the comfort air-conditioning equipment, because the operating hours and loads are driven by the process requirements and not the weather patterns and temperatures.

10.3.2.6 Checking the Results

After the complete energy and demand balances are constructed for the facility, the authors check to see if the cumulative energy/demand for these categories plus the miscellaneous category is substantially larger or smaller than the actual energy usage and demand over the year. If it is, and it is certain that all of the major energy uses have been identified, the authors know that a mistake was made somewhere in their assumptions. As mentioned above, one area that has typically been difficult to accurately survey is the energy use by motors. Measuring the actual load factors is difficult on a one-day walk-through audit visit, so the authors use the energy balance data to help estimate the likely load factors for the motors. This is done by adjusting the load factor estimates on a number of the motors to arrive at a satisfactory level of the energy and demand from the electric motors. Unless this is done, it is likely that the energy used by the motors will be overestimated, and thus overestimate the energy savings from replacing standard motors with high-efficiency motors.

As an example, the authors performed an energy audit for one large manufacturing facility with a lot of motors. It was first assumed that the load factors for the motors were approximately 80%, based on what the facility personnel explained. Using this load factor gave a total energy use for the motors of over 16 million kWh/year and a demand of over 2800 kW. Because the annual energy use for the entire facility was just over 11 million kWh/year and the demand never exceeded 2250 kW, this load factor was clearly wrong. The authors adjusted the average motor load factor to 40% for most of the motors, which reduced the energy use figure to 9 million kWh and the demand to just under 1600 kW. These values are much more reasonable with motors making up a large part of the electrical load of this facility.

After the energy/demand balances have been satisfactorily compiled, the authors use a graphics program to draw a pie chart showing the distribution of energy/demand between the various categories. This allows visual representation of which categories are responsible for the majority of the energy use. It also makes it possible to focus the energy savings analyses on the areas of largest energy use.

10.3.3 Problems with Energy Analysis Calculations

Over the course of performing 120 industrial energy audits, the authors have identified a number of problem areas. One lies with the method of calculating energy cost savings: whether to use the average cost of electricity or break the cost down into energy and demand cost components. Other problems include instances where the energy and demand savings associated with specific energy-efficiency measures may not be fully realized or where more research should go into determining the actual savings potential.

10.3.3.1 On-Peak and Off-Peak Uses: Overestimating Savings by Using the Average Cost of Electricity

One criticism of energy auditors is that they sometimes overestimate the dollar savings available from various energy-efficiency measures. One way overestimation can result is when the analyst uses only the average cost of electricity to compute the savings. Because the average cost of electricity includes a demand component, using this average cost to compute the savings for companies who operate on more than one shift can overstate the dollar savings. This is because the energy cost during the off-peak hours does not include a demand charge. A fairly obvious example of this type of problem occurs when the average cost of electricity is used to calculate savings from installing high-efficiency security lighting. In this instance, there is no on-peak electricity use, but the savings will be calculated as if all the electricity was used on-peak.

The same problem arises when an energy-efficiency measure does not result in an expected—or implicitly expected—demand reduction. Using a cost of electricity that includes demand in this instance will again overstate the dollar savings. Examples of energy-efficiency measures that fall into this category are occupancy sensors, photosensors, and adjustable-speed drives (ASDs). Although all of these measures can reduce the total amount of energy used by the equipment, there is no guarantee that the energy use will only occur during off-peak hours. While an occupancy sensor will save lighting kWh, it will not save any kW if the lights come on during the peak load period. Similarly, an ASD can save energy use for a motor, but if the motor needs its full load capability—as an air-conditioning fan motor or chilled-water pump motor might—during the peak load period, the demand savings may not be there. The reduced use of the device or piece of equipment on-peak load times may introduce a diversity factor that produces some demand savings. However, even this savings will be overestimated by using the average cost of electricity in most instances.

On the other hand, some measures can be expected to provide their full demand savings at the time of the facility's peak load. Replacing 40-W T12 fluorescent lamps with 32-W T8 lamps will provide a verifiable demand savings because the wattage reduction will be constant at all times, and will specifically show up during the period of peak demand. Shifting loads to off-peak times should also produce verifiable demand savings. For example, putting a timer or energy management system control on a constant-load electric drying oven to insure that it does not come on until the off-peak time will result in the full demand savings. Using high-efficiency motors also seems like it would also produce verifiable savings because of its reduced kW load, but in some instances, there are other factors that tend to negate these benefits. This topic is discussed later.

To help solve the problem of overestimating savings from using the average cost of electricity, the authors divide their energy savings calculations into a demand savings and an energy savings. In most instances, the energy savings for a particular piece of equipment is calculated by first determining the demand savings for that equipment and then multiplying by the total operating hours of the equipment. To calculate the annual cost savings (CS), the following formula is used:

$$\begin{aligned}\text{CS} =& [\text{Demand savings} \times \text{Average monthly demand rate} \times 12 \text{ months/year}]\\ &+ [\text{Energy savings} \times \text{Average cost of electricity without demand}].\end{aligned}$$

If a recommended measure has no demand savings, then the energy cost savings is simply the energy savings times the average cost of electricity without demand (or off-peak cost of electricity). This procedure forces us to think carefully about which equipment is used on-peak and which is used off-peak.

To demonstrate the difference in savings estimates, consider replacing a standard 30-hp motor with a high-efficiency motor. The efficiency of a standard 30-hp motor is 0.901 and a high-efficiency motor is 0.931. Assume the motor has a load factor of 40% and operates 8760 h/year (three shifts). Assume also that the average cost of electricity is \$0.068/kWh (including demand), the average demand cost is \$3.79/kW/mo, and the average cost of electricity without demand is \$0.053/kWh. The equation for calculating the demand of a motor is:

$$\text{D} = \text{HP} \times \text{LF} \times 0.746 \times 1/\text{Eff}.$$

The savings on demand (or demand reduction) from installing a high-efficiency motor is:

$$\begin{aligned}\text{DR} =& \text{HP} \times \text{LF} \times 0.746 \times (1/\text{Eff}_\text{S} - 1/\text{Eff}_\text{H}) = 30 \text{ hp} \times 0.40 \times 0.746 \text{ kW/hp}\\ &\times (1/0.901 - 1/0.931) = 0.32 \text{ kW}.\end{aligned}$$

The annual energy savings (ES) is:

$$\text{ES} = \text{DR} \times \text{H} = 0.32 \text{ kW} \times 8760 \text{ h/year} = 2803.2 \text{ kWh/year}.$$

Using the average cost of electricity above, the cost savings (CS_1) calculated as:

$$\text{CS}_1 = \text{ES} \times (\text{Average cost of electricity}) = 2803.2 \text{ kWh/year} \times 0.068/\text{kWh} = 190.62/\text{yr}.$$

Using the recommended formula above:

$$\begin{aligned}\text{CS} &= [\text{Demand savings} \times \text{Average monthly demand rate} \times 12\text{months/year}]\\ &\quad + [\text{Energy savings} \times \text{Average cost of electricity without demand}]\\ &= (0.32 \text{ kW} \times 3.79/\text{month} \times 12\text{months/year}) + (2803.2 \text{ kWh/year} \times 0.053/\text{kWh})\\ &= (14.55 + 148.57)/\text{year} = 163.12/\text{year}.\end{aligned}$$

In this example, using the average cost to calculate the energy cost savings overestimates the cost savings by \$27.50 per year, or 17%. Although the actual amount is small for one motor, if this error is repeated for all the motors for the entire facility as well as all other measures that reduce the demand component only during the on-peak hours, then the cumulative error in cost savings predictions can be substantial.

10.3.3.2 Motor Load Factors

Many in the energy-auditing business started off assuming that motors ran at full load or near full load, and based their energy consumption analysis and energy savings analysis on that premise. Most books and publications that give a formula for finding the electrical load of a motor do not even include a term for the motor load factor. However, since experience soon showed the authors that few motors actually run at full load or near full load, they were left in a quandary about what load factor to actually use in calculations, because good measurements on the actual motor load factor are rarely to be had. A classic paper by R. Hoshide shed some light on the distribution of motor load factors from his experience.[18] In this paper, Hoshide noted that only about one-fourth of all three-phase motors run with a load factor greater than 60%, with 50% of all motors running at load factors between 30 and 60%, and one-fourth running with load factors less than 30%. Thus, those auditors who had been assuming that a typical motor load factor was around 70 or 80% had been greatly overestimating the savings from high-efficiency motors, adjustable-speed drives, high-efficiency belts, and other motor-related improvements.

The energy and demand balances discussed earlier also confirm that overall motor loads in most facilities cannot be anywhere near 70%–80%. The authors' experience in manufacturing facilities has been that motor load factors are more correctly identified as being in the 30%–40% range. With these load factors, one obtains very different savings estimates and economic results than when one assumes that a motor is operating at a 70% or greater load factor, as shown in the example earlier.

One place where the motor load factor is critical—but often overlooked—is in the savings calculations for ASDs. Many motor and ASD manufacturers provide easy-to-use software that will determine savings with an ASD if you supply the load profile data. Usually a sample profile is included that shows calculations for a motor operating at full load for some period of time, and at a fairly high overall load factor—e.g., around 70%. If the motor has a load factor of only 50% or less to begin with, the savings estimates from a quick use of one of these programs may be greatly exaggerated. If the actual motor use profile with the load factor of 50% is use, one may find that the ASD will still save some energy and money, but often not as much as it looks like when the motor is assumed to run at the higher load factor. For example, a 20-hp motor may have been selected for use on a 15-hp load to insure that there is a "safety factor." Thus, the maximum load factor for the motor would be only 75%. A typical fan or pump in an air-conditioning system that is responding to outside weather conditions may operate at its maximum load only about 10% of the time. Because that maximum load here is only 15 hp, the average load factor for the motor might be more like 40%, and will not be even close to 75%.

10.3.3.3 High-Efficiency Motors

Another interesting problem area is associated with the use of high-efficiency motors. In Hoshide's paper mentioned earlier, he notes that, in general, high-efficiency motors run at a faster full-load speed than standard-efficiency motors. This means that when a standard motor is replaced by a high-efficiency motor, the new motor will run somewhat faster than the old motor in almost every instance. This is a problem for motors that drive centrifugal fans and pumps, because the higher operating speed means greater power use by the motor. Hoshide provides an example where he shows that a high-efficiency motor that should be saving about 5% energy and demand actually uses the same energy and demand as the old motor. This occurs because the increase in speed of the high-efficiency motor offsets the power savings by almost exactly the same 5% due to the cube law for centrifugal fans and pumps.

Few energy auditors ever monitor fans or pumps after replacing a standard motor with a high-efficiency motor; therefore, they have not realized that this effect has cancelled the expected energy and demand savings. Since Hoshide noted this feature of high-efficiency motors, the authors have been careful to make sure that their recommendations for replacing motors with centrifugal loads carry the notice that it will probably be necessary to adjust the drive pulleys or drive system so that the load is operated at the same speed to achieve the expected savings.

10.3.3.4 Motor Belts and Drives

The authors have developed some significant questions about the use of cogged and synchronous belts, and the associated estimates of energy savings. It seems fairly well accepted that cogged and synchronous belts do transmit more power from a motor to a load than if standard smooth V-belts are used. In some instances, this should certainly result in some energy savings. A constant-torque application like a conveyor drive may indeed save energy with a more efficient drive belt because the motor will be able to supply that torque with less effort. Consider also a feedback-controlled application, such as a thermostatically controlled ventilating fan or a level-controlled pump. In this case, the greater energy transmitted to the fan or pump should result in the task being accomplished faster than if less drive power were supplied, and some energy savings should exist. However, if a fan or a pump operates in a nonfeedback application—as is common for many motors—then there will not be any energy savings. For example, a large ventilating fan that operates at full load continuously without any temperature or other feedback may not use less energy with an efficient drive belt, because the fan may run faster as a result of the drive belt having less slip. Similarly, a pump that operates continuously to circulate water may not use less energy with an efficient drive belt. This is an area that needs some monitoring and metering studies to check the actual results.

Whether efficient drive belts result in any demand savings is another question. Because, in many cases, the motor is assumed to be supplying the same shaft horsepower with or without high-efficiency drive belts, a demand savings does not seem likely in these cases. It is possible that using an efficient belt on a motor with a constant-torque application which is controlled by an ASD might result in some demand savings. However, for the most common applications, the motor is still supplying the same load, and thus would have the same power demand. For feedback-controlled applications, there might be a diversity factor involved so that the reduced operation times could result in some demand savings—but not the full value otherwise expected. Thus, using average cost electricity to quantify the savings expected from high-efficiency drive belts could well overestimate the value of the savings. Verification of the cases where demand savings are to be expected is another area where more study and data are needed.

10.3.3.5 Adjustable-Speed Drives

The authors would like to close this discussion with a return to ASDs because these are devices that offer a great potential for savings, but have far greater complexities than are often understood or appreciated. Fans and pumps form the largest class of applications where great energy savings is possible from the use of ASDs. This is a result again of the cube law for centrifugal fans and pumps where the power required to drive a fan or pump is specified by the cube of the ratio of the flow rates involved. According to the cube law, a reduction in flow to one-half the original value could now be supplied by a motor using only one-eighth of the original horsepower. Thus, whenever an airflow or liquid flow can be reduced, such as in a variable-air-volume system or with a chilled-water pump, there is a dramatic savings possible with an ASD. In practice, there are two major problems with determining and achieving the expected savings.

The first problem is the one briefly mentioned earlier, and that is determining the actual profile of the load involved. Simply using the standard profile in a piece of vendor's software is not likely to produce very realistic results. There are so many different conditions involved in fan and pump applications that taking actual measurements is the only way to get a good idea of the savings that will occur with an ASD. Recent papers have discussed the problems with estimating the loads on fans and pumps, and have shown how the cube law itself does not always give a reasonable value.[19–21] The Industrial Energy Center at Virginia Polytechnic Institute and Virginia Power Company have developed an approach wherein they classify potential ASD applications into eight different groups, and then estimate the potential savings from analysis of each system and from measurements of that system's operation.[22] Using both an analytical approach and a few measurements allows them to get a reasonable estimate of the motor load profile, and thus a reasonable estimate of the energy and demand savings possible.

The second problem is achieving the savings predicted for a particular fan or pump application. It is not sufficient to just identify the savings potential and then install an ASD on the fan or pump motor.

In most applications, there is some kind of throttling or bypass action that results in almost the full horsepower still being required to drive the fan or pump most of the time. In these applications, the ASD will not save much, unless the system is altered to remove the throttling or bypass device and a feedback sensor is installed to tell the ASD what fraction of its speed to deliver. This means that in many airflow systems, the dampers or vanes must be removed so that the quantity of air can be controlled by the ASD changing the speed of the fan motor. In addition, some kind of feedback sensor must be installed to measure the temperature or pressure in the system to send a signal to the ASD or a PLC controller to alter the speed of the motor to meet the desired condition. The additional cost of the alterations to the system and the cost of the control system needed greatly change the economics of an ASD application compared to the case where only the purchase cost and installation cost of the actual ASD unit is considered.

For example, a dust collector system might originally be operated with a large 150-hp fan motor running continuously to pick up the dust from eight saws. However, because production follows existing orders for the product, sometimes only two, three, or four saws are in operation at a particular time. Thus, the load on the dust collector is much lower at these times than if all eight saws are in use. An ASD is a common recommendation in this case, but estimating the savings is not easy to begin with, and after the costs of altering the collection duct system and of adding a sophisticated control system to the ASD are considered, the bottom line result is much different than the cost of the basic ASD with installation. Manual or automatic dampers must be added to each duct at a saw so that it can be shut off when the saw is not running. In addition, a PLC for the ASD must be added to the new system, together with sensors added to each damper so that the PLC will know how many saws are in operation and therefore what speed to tell the ASD for the fan to run to meet the dust collection load of that number of saws. Without these system changes and control additions, the ASD itself will not save any great amount of energy or money. Adding them in might well double the cost of the basic ASD, and double the payback time that may have originally been envisioned.

Similarly, for a water or other liquid-flow application, the system piping or valving must be altered to remove any throttling or bypass valves, and a feedback sensor must be installed to allow the ASD to know what speed to operate the pump motor. If several sensors are involved in the application, then a PLC may also be needed to control the ASD. For example, putting an ASD on a chilled-water pump for a facility is much more involved, and much more costly, than simply cutting the electric supply lines to the pump motor and inserting an ASD for the motor. Without the system alterations and without the feedback control system, the ASD cannot provide the savings expected.

10.3.4 General Rules

New energy auditors often do not have the experience to have engineering judgment about the accuracy of their analyses. That is, they cannot look at the result and immediately know that it is not within the correct range of likely answers. Because the authors' IAC program has a fairly steady turnover of students, they find the same type of errors cropping up over and over as draft audit reports are reviewed. To help new team members develop the engineering judgment that they will eventually gain through experience, the authors are developing "rules of thumb" for energy analyses. The rules of thumb are intended to provide a ballpark estimate of the expected results. For example, if the rule of thumb for the percent for installing high-efficiency motors says that the savings range is 3%–5% of the energy use by the motors, then a student who comes up with a savings of 25% will immediately know that the calculations are wrong and will know to check the assumptions and data entry to see where the error lies. Without these rules of thumb, the burden for checking these results is shifted to the team leaders and program directors. Although this does not obviate the need for report review, it minimizes the likelihood that errors will occur. The authors suggest that other organizations who frequently utilize and train new energy auditors consider developing such rules of thumb for the major types of facilities or geographic areas that they audit.

Energy auditing is not an exact science, but a number of opportunities is available for improving the accuracy of the recommendations. Techniques which may be appropriate for small-scale energy audits can introduce significant errors into the analyses for large complex facilities. This chapter began by discussing how to perform an energy and demand balance for a company. This balance is an important step in doing an energy-use analysis, because it provides a check on the accuracy of some of the assumptions necessary to calculate savings potential. It also addressed several problem areas which can result in overly optimistic savings projections, and suggested ways to prevent mistakes. Finally, several areas where additional research, analysis, and data collection are needed were identified. After this additional information is obtained, everyone can produce better and more accurate energy audit results.

10.3.4.1 Decision Tools for Improving Industrial Energy Audits—OIT Software Tools

The Office of Industrial Technologies—a program operated by the U.S. Department of Energy, Division of Energy Efficiency and Renewable Energy—provides a series of computer software tools that can be obtained free from their Web site, or by ordering a CD at no cost from them. With the right know-how, these powerful tools can be used to help identify and analyze energy system savings opportunities in industrial and manufacturing plants. Although the tools are accessible at the U.S. DOE Web site for download, they also encourage users to attend a training workshop to enhance their knowledge and take full advantage of opportunities identified in the software programs. For some tools, advanced training is also available to help further increase expertise in their use.

10.3.4.2 Decision Tools for Industry—Order the Portfolio of Tools on CD

The Decision Tools for Industry CD contains the MotorMaster+(MM+), Pump System Assessment Tool, Steam System Tool Suite, 3E Plus, and the new AirMaster+software packages described here. In addition, it includes MM+training. The training walks the user through both the fundamentals and the advanced features of MM+and provides examples for using the software to make motor purchase decisions. The CD can be ordered via email from the EERE Information Center or by calling the EERE Information Center at 1-877-EERE-INF (877-337-3463).

DOE Industry Tools:

- AIRMaster+
- Chilled Water System Analysis Tool (CWSAT)
- Combined Heat and Power Application Tool (CHP)
- Fan System Assessment Tool (FSAT)
- MotorMaster+4.0
- MotorMaster+International
- NO_x and Energy Assessment Tool (NxEAT)
- Plant Energy Profiler for the Chemical Industry (ChemPEP Tool)
- Process Heating Assessment and Survey Tool (PHAST)
- Pumping System Assessment Tool 2004 (PSAT)
- Steam System Tool Suite

Other Industry Tools:

- ASDMaster: Adjustable Speed Drive Evaluation Methodology and Application

AIRMaster+. This tool provides comprehensive information on assessing compressed-air systems, including modeling, existing and future system upgrades, and evaluating savings and effectiveness of energy-efficiency measures.

Chilled Water System Analysis Tool Version 2.0. Use the CWSAT to determine energy requirements of chilled-water distribution systems, and to evaluate opportunities for energy and costs savings by applying improvement measures. Provide basic information about an existing configuration to calculate current energy consumption, and then select proposed equipment or operational changes for comparison. The results of this analysis will help the user quantify the potential benefits of chilled-water system improvements.

Combined Heat and Power Application Tool. The CHP Application Tool helps industrial users evaluate the feasibility of CHP for heating systems such as fuel-fired furnaces, boilers, ovens, heaters, and heat exchangers. It allows analysis of three typical system types: fluid heating, exhaust-gas heat recovery, and duct burner systems. Use the tool to estimate system costs and payback period, and to perform "what-if" analyses for various utility costs. The tool includes performance data and preliminary cost information for many commercially available gas turbines and default values that can be adapted to meet specific application requirements.

Fan System Assessment Tool. Use the FSAT to help quantify the potential benefits of optimizing fan system configurations that serve industrial processes. FSAT is simple and quick, and requires only basic information about the fans being surveyed and the motors that drive them. With FSAT, one can calculate the amount of energy used by one's fan system, determine system efficiency, and quantify the savings potential of an upgraded system.

MotorMaster+4.0. An energy-efficient motor selection and management tool, MotorMaster+4.0 software includes a catalog of over 20,000 AC motors. This tool features motor inventory management tools, maintenance log tracking, efficiency analysis, savings evaluation, energy accounting, and environmental reporting capabilities.

MotorMaster+International. MotorMaster+International includes many of the capabilities and features of MotorMaster+; however, now it can help evaluate repair/replacement options on a broader range of motors, including those tested under the Institute of Electrical and Electronic Engineers (IEEE) standard, and those tested using International Electrical Commission (IEC) methodology. With this tool, analyses can be conducted in different currencies, and it will calculate efficiency benefits for utility rate schedules with demand charges, edit and modify motor rewind efficiency loss defaults, and determine "best available" motors. The tool can be modified to operate in English, Spanish, and French.

NO_x and Energy Assessment Tool. The NxEAT helps plants in the petroleum refining and chemical industries to assess and analyze NO_x emissions and application of energy-efficiency improvements. Use the tool to inventory emissions from equipment that generates NO_x, and then compare how various technology applications and efficiency measure affect overall costs and reduction of NO_x. Perform "what-if" analyses to optimize and select the most cost-effective methods for reducing NO_x from systems such as fired heaters, boilers, gas turbines, and reciprocating engines.

Plant Energy Profiler for the Chemical Industry. The ChemPEP Tool provides chemical plant managers with the information they need to identify savings and efficiency opportunities. The ChemPEP Tool enables energy managers to see overall plant energy use, identify major energy-using equipment and operations, summarize energy cost distributions, and pinpoint areas for more detailed analysis. The ChemPEP Tool provides plant energy information in an easy-to-understand graphical manner that can be very useful to managers.

Process Heating Assessment and Survey Tool. The PHAST provides an introduction to process heating methods and tools to improve thermal efficiency of heating equipment. Use the tool to survey process-heating equipment that uses fuel, steam, or electricity, and identify the most energy-intensive equipment. It can also help perform an energy (heat) balance on selected equipment (furnaces) to identify and reduce nonproductive energy use. Compare performance of the furnace under various operating conditions and test "what-if" scenarios.

Pumping System Assessment Tool 2004. The Pumping System Assessment Tool helps industrial users assess the efficiency of pumping system operations. PSAT uses achievable pump performance data from Hydraulic Institute standards and motor performance data from the MotorMaster+database to calculate potential energy and associated cost savings.

Steam System Tool Suite. In many industrial facilities, steam system improvements can save 10%–20% in fuel costs. To help tap into potential savings in typical industrial facilities, DOE offers a suite of tools for evaluating and identifying steam system improvements.

- *Steam System Assessment Tool (SSAT) Version 2.0.0*. The SSAT allows steam analysts to develop approximate models of real steam systems. Using these models, SSAT can be applied to quantify the magnitude—energy, cost, and emission savings—of key potential steam improvement opportunities. SSAT contains the key features of typical steam systems. The enhanced and improved version includes features such as a steam demand savings project; a user-defined fuel model; a boiler stack loss worksheet for the SSAT fuels; a boiler flash steam recovery model; and improved steam-trap models.
- *3E Plus, Version 3.2*. The program calculates the most economical thickness of industrial insulation for user input operating conditions. Calculations can be made using the built-in thermal performance relationships of generic insulation materials or supply conductivity data for other materials.
- *Steam Tool Specialist Qualification Training*. Industry professionals can earn recognition as Qualified Specialists in the use of the BestPractices Steam Tools. DOE offers an in-depth two-and-a-half-day training session for steam system specialists, including two days of classroom instruction and a written exam. Participants who complete the workshop and pass the written exam are recognized by DOE as Qualified Steam Tool Specialists. Specialists can assist industrial customers in using the BestPractices Steam Tools to evaluate their steam systems.

ASDMaster: Adjustable Speed Drive Evaluation Methodology and Application. This Windows™ software program helps plant or operations professionals determine the economic feasibility of an ASD application, predict how much electrical energy may be saved by using an ASD, and search a database of standard drives. The package includes two 3.5-inch diskettes, a user's manual, and a user's guide. Please order from EPRI. For more information, see the ASDMaster Web Site.

10.3.4.3 Energy-Auditing Help From Industrial Assessment Centers

The Industrial Assessment Centers (IACs), sponsored by the U.S. Department of Energy, Energy Efficiency and Renewable Energy Division (EERE) Industrial Technologies Program (ITP), provide eligible small- and medium-sized manufacturers with no-cost energy assessments. Additionally, the IACs serve as a training ground for the next generation of energy savvy engineers.

Teams composed mainly of engineering faculty and students from the centers, located at 26 universities around the country, conduct energy audits or industrial assessments and provide recommendations to manufacturers to help them identify opportunities to improve productivity, reduce waste, and save energy. Recommendations from industrial assessments have averaged about $55,000 in potential annual savings for each manufacturer.

As a result of performing these assessments, upper-class and graduate engineering students receive unique hands on assessment training and gain knowledge of industrial process systems, plant systems, and energy systems, making them highly attractive to employers.

To be eligible for an IAC assessment, a manufacturing plant must meet the following criteria:

- Within Standard Industrial Codes (SIC) 20–39
- Generally be located within 150 miles of a host campus
- Gross annual sales below $100 million
- Fewer than 500 employees at the plant site
- Annual energy bills more than $100,000 and less than $2.5 million
- No professional in-house staff to perform the assessment

FIGURE 10.5 Industrial Assessment Center (IAC) locations and service areas. (From U.S. Department of Energy, Office of Industrial Technologies, 2005, http://www.oit.doe.gov/iac/schools.shtml.)

Presently (2007), there are 26 schools across the country participating in the IAC Program. For additional information or to apply for an assessment, go to http://www.oit.doe.gov/iac/schools.shtml and click on one of the school names for contact information. A map of the IAC centers and their service areas is shown in Figure 10.5.

10.4 Industrial Electricity End Uses and Electrical Energy Management

10.4.1 The Importance of Electricity in Industry

Electricity use in industry is primarily for electric drives, electrochemical processes, space heating, lighting, and refrigeration. Table 10.2 lists the relative importance of use of electricity in the industrial sector. Timely data on industrial and manufacturing energy use is difficult to obtain, since its frequency of collection is only every three years, and then it takes EIS another three years to process the results. In addition, it is only a sample survey, so the accuracy of the data is less that what would be optimal. However, it is better data than is available for most countries in the world. The most recent, detailed data on manufacturing energy end use (as of early 2005) is still the 1998 MECS (Manufacturing Energy Consumption Survey) data. Table 10.2 shows the electrical energy consumed for different end uses in 1998.

Because several of the categories above involve motor use, the total manufacturing energy use for motors is actually the sum of several categories:

Machine drives	53.8%
Facility HVAC	8.3%
Process cooling and refrigeration	6.0%
Onsite transportation	0.1%
Total motors	68.2%

This gives the same results shown as the pie chart shown in Figure 10.3.

TABLE 10.2 Manufacturing Electricity by End Use, 1998

	GWh	Percent Use
Machine drives (motors)	551,318	53.8
Electrochemical processes	103,615	10.1
Process heat	106,330	10.4
Facility HVAC (motors)	84,678	8.3
Facility lighting	66,630	6.5
Process cooling and refrigeration	61,263	6.0
Onsite transportation (motors)	1427	0.1
Other process	3882	0.4
Other	46,005	
Total	1,025,148	100

Source: From Manufacturing Energy Consumption Survey, 1998; U.S. Department of Energy; Energy Information Agency, 2002.

10.4.2 Electric Drives

Electric drives of one type or another use 68% of industrial electricity. Examples include electric motors, machine tools, compressors, refrigeration systems, fans, and pumps. Improvements in these applications would have a significant effect on reducing industrial electrical energy.

Motor efficiency can be improved in some cases by retrofit (modifications, better lubrication, improved cooling, heat recovery), but generally requires purchasing of more efficient units. For motors in the sizes 1–200 hp, manufacturers today supply a range of efficiency. Greater efficiency in a motor requires improved design, more costly materials, and generally greater first cost. Losses in electric-drive systems may be divided into four categories:

	Typical Efficiency (%)
Prime mover (motor)	10–95
Coupling (clutches)	80–99
Transmission	70–95
Mechanical load	1–90

Each category must be evaluated to determine energy management possibilities. In many applications the prime mover will be the most efficient element of the system. Table 10.3 shows typical induction motor data, illustrating the improvement in efficiency due to the 1992 Energy Policy Act. Note that both efficiency and power factor decrease with partial load operation, which means that motors should be sized to operate at or near full load ratings.

TABLE 10.3 Typical Electric Motor Data

	Full Load Efficiency (%)	
Size (hp)	1975	1993 (EPACT)
1	76	82.5–85.5
2	80	84.0–86.5
5	84	87.5–89.5
10	85	89.5–91.7
20	85	91.0–93.0
40	85	93.0–94.5
100	91	94.1–95.4
200	90	95.0–96.2

Manufacturers have introduced new high-efficiency electric motors in recent years. Many utilities offer rebates of \$5–\$20 per horsepower for customers installing these motors.

10.4.2.1 Electrochemical Processes

Industrial uses of electrochemical processes include electrowinning, electroplating, electrochemicals, electrochemical machining, fuel cells, welding, and batteries.

A major use of electrolytic energy is in electrowinning—the electrolytic smelting of primary metals such as aluminum and magnesium. Current methods require on the order of 13–15 kWh/kg; efforts are under way to improve electrode performance and reduce this to 10 kWh/kg. Recycling now accounts for one-third of aluminum production; this requires only about 5% of the energy required to produce aluminum from ore.

Electrowinning is also an important low-cost method of primary copper production. Another major use of electrochemical processes is in the production of chlorine and sodium hydroxide from salt brine. Electroplating and anodizing are two additional uses of electricity of great importance. Electroplating is basically the electrodeposition of an adherent coating upon a base metal. It is used with copper, brass, zinc, and other metals. Anodizing is roughly the reverse of electroplating, with the workpiece (aluminum) serving as the anode. The reaction progresses inward from the surface to form a protective film of aluminum oxide on the surface.

Fuel cells are devices for converting chemical energy to electrical energy directly through electrolytic action. Currently they represent a small use of energy, but research is directed at developing large systems suitable for use by electric utilities for small dispersed generation plants. Batteries are another major use of electrolytic energy, ranging in size from small units with energy storage in the joule or fractional joule capacity up to units proposed for electric utility use that will store 18×10^9 J (5 MWh). Electroforming, etching, and welding are forms of electrochemical used in manufacturing and material shaping. The range of applications for these techniques stretches from microcircuits to aircraft carriers. In some applications, energy for machining is reduced and reduction of scrap also saves energy. Welding has benefits in the repair and salvage of materials and equipment, reducing the need for energy to manufacture replacements.

10.4.2.2 Electric Process Heat

Electricity is widely used as a source of process heat due to ease of control, cleanliness, wide range in unit capacities (watts to megawatts), safety, and low initial cost. Typical heating applications include resistance heaters (metal sheath heaters, ovens, furnaces), electric salt bath furnaces, infrared heaters, induction and high-frequency resistance heating, dielectric heating, and direct arc electric furnaces.

Electric-arc furnaces in the primary metals industry are a major use of electricity. Typical energy use in a direct arc steel furnace is about 2.0 kWh/kg. Electric-arc furnaces are used primarily to refine recycled scrap steel. This method uses about 40% of the energy required to produce steel from iron ore using basic oxygen furnaces. Energy savings can be achieved by using waste heat to preheat scrap iron being charged to the furnace.

Glass making is another process that uses electric heat. An electric current flows between electrodes placed in the charge, causing it to melt. Electric motors constitute a small part of total glass production. Major opportunities for improved efficiency with electric process heat applications in general include improved heat transfer surfaces, better insulation, heat recovery, and improved controls.

10.4.2.3 HVAC

Heating, ventilating, and air-conditioning (HVAC) is an important use of energy in the industrial sector. The environmental needs in an industrial operation can be quite different from residential or commercial operations. In some cases, strict environmental standards must be met for a specific function or process. More often, the environmental requirements for the process itself are not limiting, but space conditioning is a prerequisite for the comfort of production personnel. Chapters 5 and 6 have a more complete discussion of energy management opportunities in HVAC systems.

10.4.2.4 Lighting

Industrial lighting needs range from low-level requirements for assembly and welding of large structures (such as shipyards) to the high levels needed for manufacture of precision mechanical and electronic components such as integrated circuits. Lighting uses about 20% of U.S. electrical energy and 7% of all energy. Of all lighting energy about 20% is industrial, with the balance being sizes of systems, energy management opportunities in industrial lighting systems are similar to those in residential/commercial systems (see Chapter 5).

10.4.2.5 Electric Load Analysis

The energy audit methodology is a general tool that can be used to analyze energy use in several forms and over a short or long period of time. Another useful technique, particularly for obtaining a short-term view of industrial electricity use, is an analysis based on evaluation of the daily load curve. Normally this analysis uses metering equipment installed by the utility and therefore available at the plant. However, special metering equipment can be installed if necessary to monitor specific process or building.

For small installations both power and energy use can be determined from the kilowatt hour meter installed numbered the equations. Please by the utility. Energy in kWh is determined by

$$E = (0.001)(K_\mathrm{h} P_\mathrm{t} C_\mathrm{t} N)\mathrm{kWh} \tag{10.1}$$

where E = electric energy used, kwh; K_h = meter constant, watt hours/revolution; P_t = potential transformer ratio; C_t = current transformer ratio; and N = number of revolutions of the meter disk. (The value of K_h is usually marked on the meter. P_t and C_t are usually 1.0 for small installations.) To determine energy use, the meter would be observed during an operation and the number of revolutions of the disk counted. Then the equation can be used to determine E.

To determine the average load over some period p (hours), determine E as earlier for time p and then use the relation that

$$L = \frac{E}{p}\ \mathrm{kW} \tag{10.2}$$

where E is in kWh, p is in hours, and L is the load in kW. Larger installations will have meters with digital outputs or strip charts. Often these will provide a direct indication of kWh and kW as a function of time. Some also indicate the reactive load (kVARs) or the power factor.

The first step is to construct the daily load curve. This is done by obtaining kWh readings each hour using the meter. The readings are then plotted on a graph to show the variation of the load over a 24-hour period. Table 10.4 shows a set of readings obtained over a 24-hour period in the XYZ manufacturing plant located in Sacramento, California and operating one shift per day. These readings have been plotted in Figure 10.6.

Several interesting conclusions can be immediately drawn from this figure:

- The greatest demand for electricity occurs at 11:00.
- Through the lunch break the third highest demand occurs.
- The ratio of the greatest demand to the least demand is approximately 3:1.
- Only approximately 50% of the energy used actually goes into making a product (54% on-shift use, 46% off-shift use).

When presented to management, these facts were of sufficient interest that a further study of electricity use was requested. Additional insight into the operation of a plant (and into the cost of purchase of electricity) can be obtained from the load analysis. Following a brief discussion of electrical load parameters, a load analysis for the XYZ Company will be described.

Any industrial electrical load consists of lighting, motors, chillers, compressors, and other types of equipment. The sum of the capacities of this equipment, in kW, is the *connected* load. The actual load at any point in time is normally less that the connected load since every motor is not turned on at the same

TABLE 10.4 Kilowatt Hour Meter Readings for XYZ Manufacturing Company

Time Meter Read	Elapsed kWh	Notes Concerning Usage	Percentage of Total Usage (%)
1:00 (a.m.)	640		
2:00	610		
3:00	570		
4:00	570	7 h preshift use	
5:00	640		
6:00	770		
7:00	1120		
Subtotal	4920		17
8:00	1470		
9:00	1700		
10:00	1790		
11:00	1850		
	(Peak)	9 h on-shift use	
12:00 (noon)	1830		
13:00 (1 p.m.)	1790		
14:00 (2 p.m.)	1790		
15:00 (3 p.m.)	1760		
16:00 (4 p.m.)	1690		
Subtotal	15,670		54
17:00 (5 p.m.)	1470		
18:00 (6 p.m.)	1310		
19:00 (7 p.m.)	1210		
20:00 (8 p.m.)	1090	8 h postshift use	
21:00 (9 p.m.)	960		
22:00 (10 p.m.)	800		
23:00 (11 p.m.)	730		
24:00 (12 a.m.)	640		
Subtotal	8210		29
Grand totals	28,800		100

time; only part of the lights may be on at any one time, and so on. Thus the load is said to be diversified, and a measure of this can be found by calculating a *diversity factor*:

$$\mathrm{DV} = \frac{(D_{m1} + D_{m2} + D_{m3} + \cdots)}{(D_{\max})} \tag{10.3}$$

where D_{m1}, D_{m2}, and so on = sum of maximum demand of individual loads in kW and $D_{\max}$ = maximum demand of plant in kW. If the individual loads do not occur simultaneously (usually they do not), the diversity factor will be greater than unity. Typical values for industrial plants are 1.3–2.5.

If each individual load operated to its maximum extent simultaneously, the *maximum* demand for power would be equal to the connected load and the diversity factor would be 1.0. However, as pointed out earlier, this does not happen except for special cases. The demand for power varies over time as loads are added and removed from the system. It is usual practice for the supplying utility to specify a demand interval (usually 0.25, 0.5, or 1.0 h) over which it will calculate the

$$D = \frac{E}{p}\ \mathrm{kW} \tag{10.4}$$

where D = demand in kW, E = kilowatt-hours used during p, and p = demand interval in hours. The demand calculated in this manner is an average value, being greater than the lowest instantaneous demand during the demand interval but less than the maximum demand during the interval.

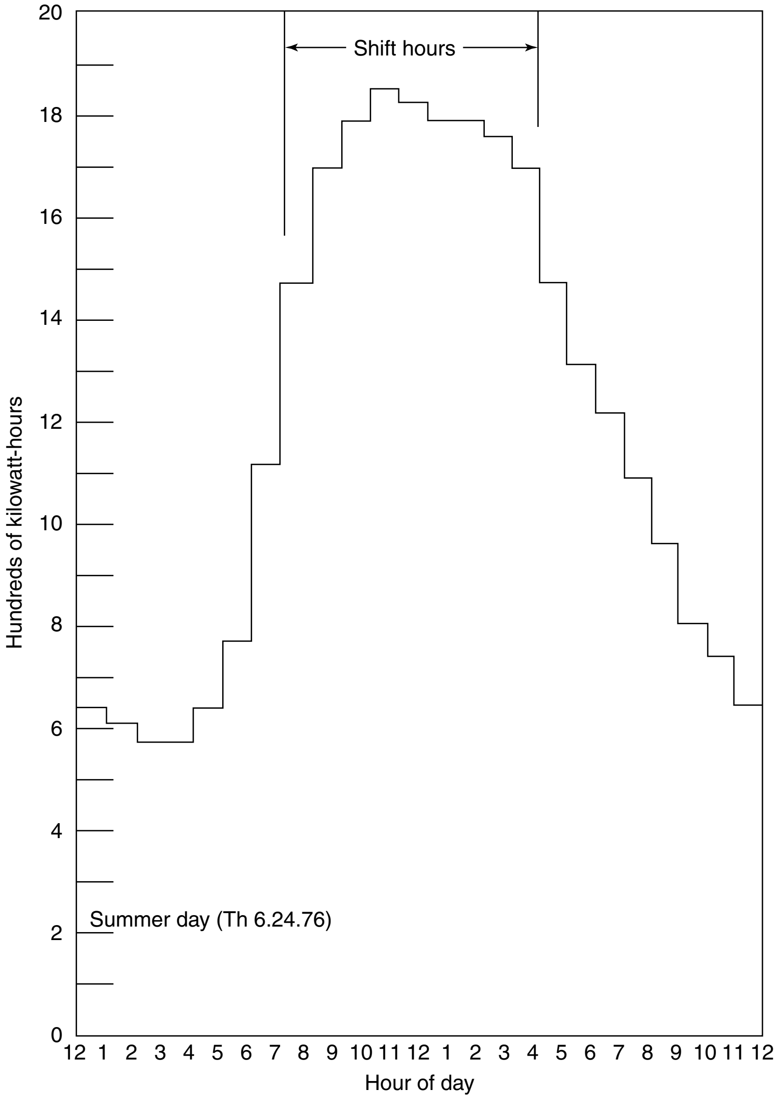

FIGURE 10.6 Daily load curve for XYZ company.

Utilities are interested in *peak demand*, since this determines the capacity of the equipment they must install to meet the customer's power requirements. This is measured by a demand factor, defined as

$$\mathrm{DF} = \frac{D_{\max}}{\mathrm{CL}} \tag{10.5}$$

where $D_{\max}$ = maximum demand in kW and CL = connected load in kW. The demand factor is normally less than unity; typical values range from 0.25 to 0.90.

Since the customer normally pays a premium for the maximum load placed on the utility system, it is of interest to determine how effectively the maximum load is used. The most effective use of the equipment would be to have the peak load occur at the start of the use period and continue unchanged throughout it. Normally, this does not occur, and a measure of the extent to which the maximum demand is sustained throughout the period (a day, month, or year) is given by the *hours use of demand*:

$$\text{HUOD} = \frac{E}{D_{\max}} \text{ hours} \tag{10.6}$$

where HUOD = hours use of demand in hours; E = energy used in period p, in kWh; $D_{\max}$ = maximum demand during period p, in kW, and p = period over which HUOD is determined—for example, 1 day, 1 month, or 1 year (p is always expressed in *hours*).

The *load factor* is another parameter that measures the plant's ability to use electricity efficiently. In effect it measures the ratio of the average load for a given period of time to the maximum load which occurs during the same period. The most effective use results when the load factor is as high as possible once E or HUOD has been minimized (it is always less than one). The load factor is defined as

$$\text{LF} = \frac{E}{(D_{\max})(p)} \tag{10.7}$$

where LF = load factor (dimensionless); E = energy used in period p in kWh; $D_{\max}$ = maximum demand during period p in kW; and p = period over which load factor is determined (e.g., 1 day, 1 month, or 1 year) in hours. Another way to determine LF is from the relation

$$\text{LF} = \frac{\text{HUOD}}{p} \tag{10.8}$$

Still another method is to determine the average load, L = kWh/p during p divided by p and then use the relation

$$\text{LF} = \frac{L}{D_{\max}} \tag{10.9}$$

These relations are summarized for convenience in Table 10.5.

TABLE 10.5 Summary of Load Analysis Parameters

Formulas	Definitions
$E = K_h P_t C_t N/1,000$	E = Electric energy used in period p, kWh
$L = E/P$	$E_{\max}$ = Maximum energy used during period p, kWh
$DV = (D_{m1} + D_{m2} + D_{m3})/D_{\max}$	K_h = Meter constant, watt hours/revolution
$D = E/P$ $D_{\max} = E_{\max}/P$	P_t = Potential transformer ratio
$DF = D_{\max}/CL$	C_t = Current transformer ratio
$\text{HUOD} = E/D_{\max}$	N = Number of revolutions of the meter disk
$LF = \frac{E}{(D_{\max})(p)} = \frac{\text{HUOD}}{p} = \frac{L}{D_{\max}}$	L = Average load, kW
	p = Period of time used to determine load, demand, electricity use, etc., normally 1 hour, day, month, or year; measured in hours
	DV = Diversity factor, dimensionless
	$D_{\max}$ = Maximum demand in period p, kW
	D_{m1}, D_{m2}, etc. = Maximum demand of individual load, kW
	D = Demand during period p, kW
	DF = Demand factor for period p, dimensionless
	CL = Connected load, kW
	HUOD = Hours use of demand during period p, hours
	LF = Load factor during period p, dimensionless

TABLE 10.6 Data for Load Analysis of XYZ Plant

p	$=24$ h
E	$=28{,}800$ kWh/day
$E_{\max}$	$=1850$ kWh
CL	$=2792$ kW
D_{m1}, D_{m2}, etc.	$=53$, 62, 144, 80, 700, 1420 kW

Returning to the XYZ plant, the various load parameters can now be calculated. Table 10.6 summarizes the needed data and the results of the calculations. The most striking thing shown by the calculations is the hours use of demand, equal to 15.6. This is a surprise, since the plant is only operating one shift. The other significant point brought out by the calculations is the low load factor.

An energy audit of the facility was conducted and the major loads were evaluated number of energy management opportunities whereby both loads (kW) and energy use (kWh) could be reduced. The audit indicated that inefficient lighting (on about 12 h per day) could be replaced in the parking lot. General office lighting was found to be uniformly at 100 fc; by selective reduction and task lighting the average level could be reduced to 75 fc or less. The air-conditioning load would also be reduced. Improved controls could be installed to automatically shut down lighting during off-shift and weekend hours (the practice had been to leave the lights on). Some walls and ceilings were selected for repainting to improve reflectance and reduced lighting energy. It was found that the air-conditioning chillers operated during weekends and off-hours; improved controls would prevent this. Also, the ventilation rates were found to be excessive and could be reduced. In the plant, compressed-air system leaks, heat losses from plating tanks, and on-peak operation of the heat treat furnace represented energy and load management opportunities.

The major energy management opportunities were evaluated to have the following potential savings, with a total payback of 5.3 months, as shown in Table 10.7 the average daily savings of electricity amounted to approximately 4400 kWh/day. This led to savings of $80,000 per year, with the cost of the modification being $36,000.

This can be compared to the original situation (Table 10.4). See also Figure 10.7, which shows the daily load curve after the changes have been made. The percentage of use on-shift is now higher. Note that $D_{\max}$ has been improved significantly (reduced by 13%); the HUOD has improved slightly (about 3% lower now); and the LF is slightly lower. Furthermore improvements are undoubtedly still possible in this facility; they should be directed first at reducing nonessential uses, thereby reducing HUOD.

So far the discussion has dealt entirely with power and has neglected the reactive component of the load. In the most general case the apparent power in kVA that must be supplied to the load is the sum of the active power in kW and the *reactive power* in KVAR (the reader who is unfamiliar with these terms should refer to a basic electrical engineering text):

$$|S| = \sqrt{P^2 + Q^2} \tag{10.10}$$

where $S=$apparent power in kVA; $P=$active power in kW; and Q=reactive power in KVAR. In this notation the apparent power is a vector of magnitude S and angle θ where θ is commonly referred to as the phase angle and given as

$$\theta = \tan^{-1}(\text{KVAR/kW}) \tag{10.11}$$

Another useful parameter is the *power factor*, given by

$$\text{pf} = \cos\theta \tag{10.12}$$

TABLE 10.7 Sample Calculations for XYZ Plant

1. $D_{\max} = \dfrac{E_{\max}}{p} = \dfrac{1,850\ \text{kWh}}{1\ \text{hr}} = 1,850\ \text{kW}$

2. $DV = \dfrac{D_{m1} + D_{m2} + D_{m3} + \ldots}{D_{\max}} = \dfrac{2,459}{1,850} = 1.33$

3. $DF = \dfrac{D_{\max}}{CL} = \dfrac{1,850}{2,792} = 0.66$

4. $\text{HOUD}_{(\text{daily})} = \dfrac{E}{D_{\max}} = \dfrac{28,800\ \text{kWh/day}}{1,850\ \text{kW}} = 15.6\ \text{hr/day}$

5. $LF_{(\text{daily})} = \dfrac{\text{HUOD}}{p} = \dfrac{15.6}{24.0} = 0.65$

The load parameters after the changes were made can be found:

$$D_{\max} = \frac{1,850 - 235}{1\ \text{hr}} = 1,615\ \text{kW}$$

$$\text{HOUD} = \frac{24,400\ \text{kWh/day}}{1,615\ \text{kW}} = 15.1\ \text{hr/day}$$

$$LF = \frac{15.1}{24} = 0.63$$

	Savings	
Calculated Savings	kW	kWh/yr
More efficient parking lot lighting	16	67,000
Reduce office lighting	111	495,000
Office lighting controls to reduce off-shift use	—	425,000
Air-conditioning controls and smaller fan motor	71	425,000
Compressed-air system repairs and reduction of heat losses from plating tanks	—	200,000
Shift heat treat oven off-peak	37	—
Totals	235	1,612,000

The revised electricity use was found to be:

	kWh	%
Preshift	4400	18
On-shift	14,400	59
Postshift	5600	23
Totals	24,400	100

The power factor is also given by

$$\text{pf} = \frac{|P|}{|S|} \tag{10.13}$$

The power factor is always less than or equal to unity. A high value is desirable because it implies a small reactive component to the load. A low value means the reactive component is large.

The importance of the power factor is related to the reactive component of the load. Even though the reactive component does not dissipate power (it is stored in magnetic or electric fields), the switch gear and distribution system must be sized to handle the current required by the apparent power, or the vector sum of the active and reactive components. This results in a greater capital and operating expense. The operating expense is increased due to the standby losses that occur in supplying the reactive component of the load.

The power factor can be improved by adding capacitors to the load to compensate for part of the inductive reactance. The benefit of this approach depends on the economics of each specific case and generally requires a careful review or analysis.

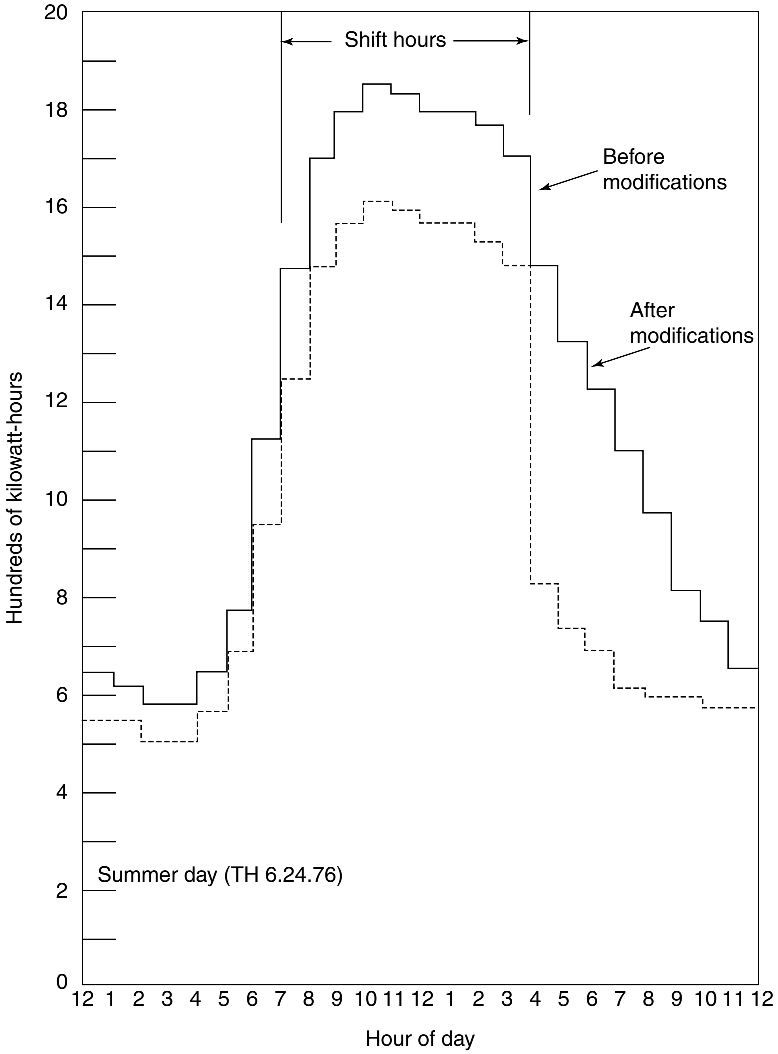

FIGURE 10.7 Daily load curve for XYZ company after modifications.

These points can be clarified with an example. Consider the distribution system shown in Figure 10.8. Four loads are supplied by a 600 A bus. Load A is a distant load that has a large reactive component and a low power factor (pf=0.6). To supply the active power requirement of 75 kW, an apparent power of 125 kVA must be provided and a current of 150 A is required.

The size of the wire to supply the load is dictated by the current to be carried and voltage drop considerations. In this case, #3/0 wire that weighs 508 lb per 1000 ft. and has a resistance of 0.062 Ω per 1000 ft. is used. Since the current in this conductor is 150 A, the power dissipated in the resistance of the conductor is

$$P = \sqrt{3}i^2 r = (1.732)(150^2)(0.124)\text{W}$$

$$P = 4.8 \text{ kW}$$

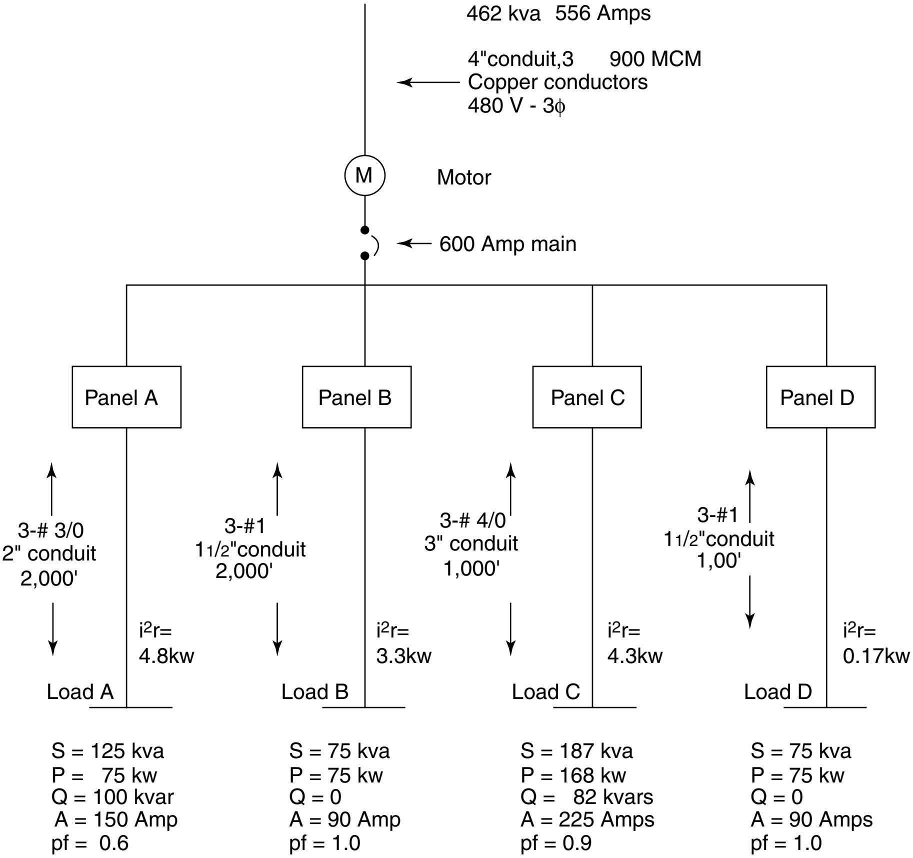

FIGURE 10.8 Electrical diagrams for building 201, XYZ company.

Similar calculations can be made for load B, which uses #1 wire, at 253 lb per 1000 ft. and 0.12 Ω/1000 ft.

Now the effect of the power factor is visible. Although the active power is the same for both load A and load B, load A requires 150 A vs. 90 A for load B. The i^2r standby losses are also higher for load A as opposed to load B. The installation cost to service load B is roughly half that of load A, due to the due to the long conduit run of load B compared to load D. For large loads that are served over long distances and operate continuously, consideration should be given to using larger wire sizes to reduce standby losses.

An estimate of the annual cost of power dissipated as heat in these conduit runs can be made if the typical operating hours of each load are known:

Load	Line Losses in kW	Operating Hours/yr	kWh/year
A	4.8	2000	9600
B	3.3	2000	6600
C	4.3	4000	17,200
D	0.17	2000	340
Total			33,740

At an average cost of 6¢/kWh (includes demand and energy costs), the losses in the distribution system alone are $2022 per year. Over the life of the facility, this is a major expense for a totally unproductive use of energy.

10.4.2.6 Data Acquisition and Control Systems for Energy Management

Data acquisition is essential in energy management for at least three reasons: (1) base-line operational data is an absolute requirement for understanding the size and timing of energy demands for each plant, division, system, and component, and design of the energy management strategy; (2) continuing data acquisition during the course of the energy conservation effort is necessary to calculate the gains made in energy-use efficiency and to measure the success of the program; and (3) effective automatic control depends upon the accurate measurement of the controlled variables and the system operational data. More information on control systems can be found in Chapter 6.

With small, manually controlled systems, data acquisition is possible using indicating instruments and manual recording of data. With large systems, or almost any size automatically controlled system, manual data collection is impractical. The easy availability and the modest price of personal digital computers (PCs) and their present growth in speed and power as their price declines makes them the preferred choice for data acquisition equipment. The only additions needed to the basic PC are the video monitor; a mass data storage device (MSD), analog to digital (A/D) interface cards; software for controlling the data sampling, data storage, and data presentation; and a suitable enclosure for protecting the equipment from the industrial environment.

That same computer is also suitable for use as the master controller of an automatic control system. Both functions can be carried on simultaneously, with the same equipment, with a few additions necessary for the control part of the system. These additional electronic components include multiplexers to increase the capacity of the A/D cards; direct memory access (an addition to the A/D boards), which speeds operation by allowing the data transfer to bypass the CPU and programmable logic controllers (PLCs); and digital input/output cards (I/Os), both used for controlling the equipment controllers. The most critical parts of either the data acquisition or the control system are the software. The hardware can be ordered off-the-shelf; but the software must be either written from scratch or purchased and modified for each particular system in order to achieve the reliable, high-performance operation that is desired. Although many proprietary program languages exist for the PCs and PLCs used for control purposes, BASIC is the most widely used. A schematic diagram of a typical data acquisition and control system is shown in Figure 10.9.

A major application has been in the control of mechanical and electrical systems in commercial and industrial buildings. These have been used to control lighting, electric demand, ventilating fans, thermostat setbacks, air-conditioning systems, and the like. These same computer systems can also be used in industrial buildings with or without modification for process control. Several manufactures of the computer systems will not only engineer and install the system but will maintain and operate it from a remote location. Such operations are ordinarily regional. For large systems in large plants, one may be able to have the same service provided in-plant. However, there are also many small standalone analog control systems that can be used advantageously for the control of simple processes. Examples of these are a temperature controller using a thermocouple output to control the temperature of a liquid storage tank; a level controller, which keeps the liquid level in a tank constant by controlling a solenoid valve; and an oxygen trim system for a small boiler, which translates the measurement of the oxygen concentration in the exhaust stream into the jack shaft position, which regulates the combustion airflow to the burner.

After installing a demand limiter on an electric-arc foundry cupola, the manager was able to reduce the power level from 7100 kW to 4900 kW with negligible effect on the production time and no effect on product quality. The savings in demand charges alone were $4400 per month with an additional savings in energy costs.

10.4.3 Web-Based Facility Automation Systems

Of all recent developments affecting computerized energy management systems, the most powerful new technology to come into use in the last several years has been information technology, or IT. The combination of cheap, high-performance microcomputers, together with the emergence of high-capacity communication lines, networks, and the Internet has produced explosive growth in IT and its

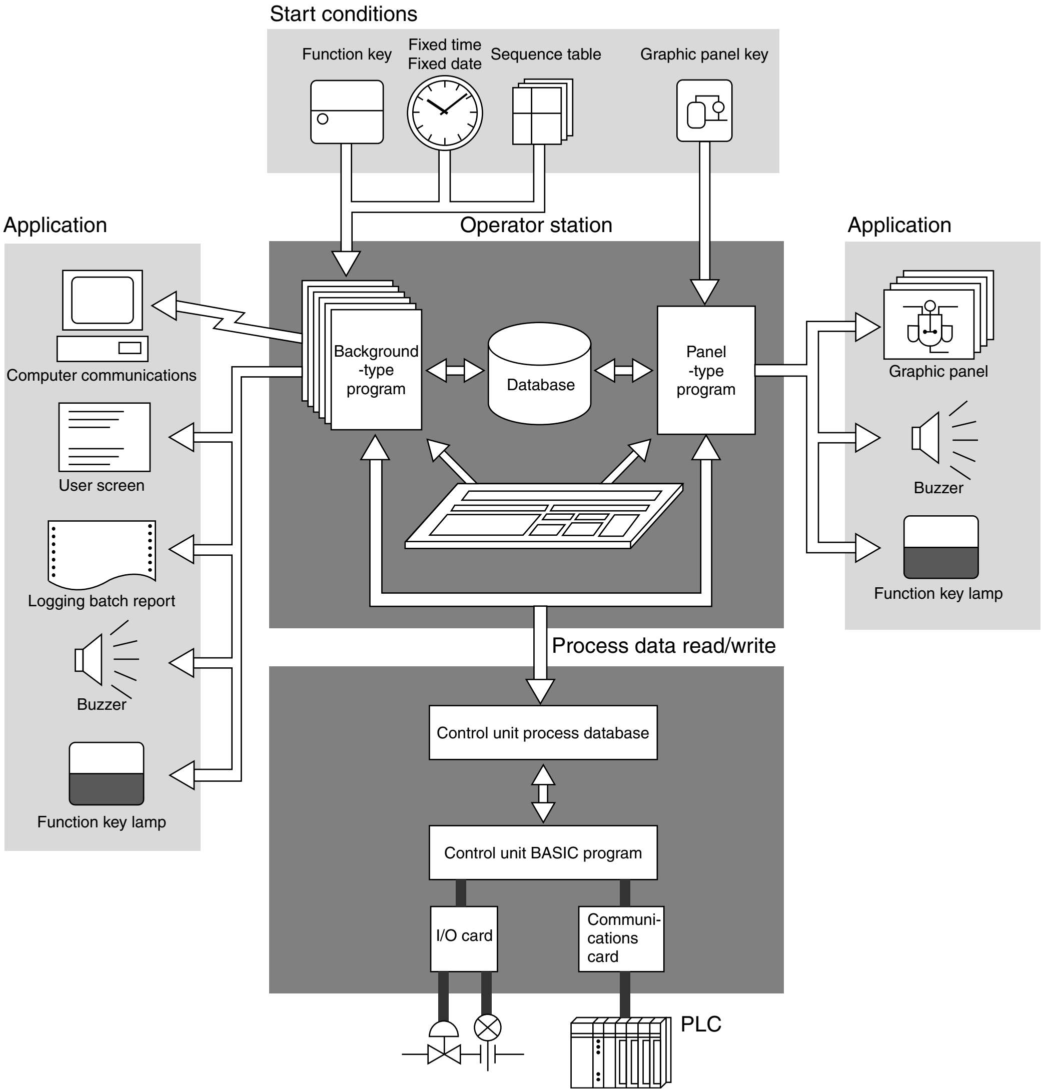

FIGURE 10.9 Typical data acquisition and control system.

application throughout the U.S. economy. Energy information and control systems have been no exception. IT and Internet-based systems are the wave of the future. Almost every piece of equipment and almost every activity will be connected and integrated into the overall facility operation in the next several years.[23]

In particular, the future of DDC in facility automation systems (FAS) can be found on the Web. Almost all FAS manufacturers see the need to move their products to the Internet. Tremendous economies of scale and synergies can be found there. Manufacturers no longer have to create the transport mechanisms for data to flow within a building or campus. They just need to make sure their equipment can utilize the network data paths already installed or designed for a facility. Likewise, with the software to display data to users, manufacturers that take advantage of presentation layer standards such as HTML and JAVA can provide the end user with a rich, graphical, and intuitive interface to their FAS using a standard Web browser.

Owners will reap the benefits of Internet standards through a richer user interface, more competition among FAS providers, and the ability to use their IT infrastructure to leverage the cost of transporting data within a facility. Another area where costs will continue to fall in using Internet standards is the hardware required to transport data within a building or a campus. Off-the-shelf products such as routers, switches, hubs, and server computers make the FAS just another node of the IT infrastructure. Standard IT tools can be used to diagnose the FAS network, generate reports of FAS bandwidth on the intranet, and back up the FAS database.

The FAS of old relied heavily on a collection of separate systems that operated independently, and often with proprietary communication protocols that made expansion, modification, updating, and integration with other building or plant information and control systems very cumbersome, if not impossible. Today, the FAS is not only expected to handle all of the energy- and equipment-related tasks, but also to provide operating information and control interfaces to other facility systems, including the total facility or enterprise management system.

Measuring, monitoring, and maximizing energy savings is a fundamental task of all FAS, and is the primary justification for many FAS installations. Improving facility operations in all areas, through enterprise information and control functions, is fast becoming an equally important function of the overall FAS or facility management system. The Web provides the means to share information easier, quicker, and cheaper than ever before. There is no doubt that the Web is having a huge impact on the FAS industry. The FAS of tomorrow will rely heavily on the Web, TCP/IP, high-speed data networks, and enterprise-level connectivity. If it has not already been done, it is a good time for energy managers to get to know their IT counterparts at their facility, along with those in the accounting and maintenance departments. The future FAS will be here sooner than you think.[24]

10.4.3.1 Energy Management Strategies for Industry

Energy management strategies for industry can be grouped into three categories:

- Operational and maintenance strategies
- Retrofit or modification strategies
- New design strategies

The order in which these are listed corresponds approximately to increased capital investment and increased implementation times. Immediate savings at little or no capital cost can generally be achieved by improved operations and better maintenance. Once these “easy” savings have been realized, additional improvements in efficiency will require capital investments.

10.4.3.2 Electric Drives and Electrically Driven Machinery

About 68% of industrial electricity use is for electrical-motor-driven equipment. Integral horsepower (<0.75 kW) motors are more numerous. Major industrial motor loads are, in order of importance, pumps, compressors, blowers, fans, miscellaneous integral motor applications including conveyors, DC drives, machine tools, and fractional horsepower applications.

Numerous examples of pumping in industry can be observed. These include process pumping in chemical plants, fluid movement in oil refineries, and cooling water circulation. An example of compressors is in the production of nitrogen and oxygen, two common chemicals. Large amounts of electricity are used to drive the compressors, which supply air to the process.

The typical industrial motor is a polyphase motor rated at 11.2 kW (15 hp) and having a life of about 40,000 h. The efficiencies of electric motors have increased recently as a result of higher energy prices, conservation efforts, and new government standards (the Energy Policy Act). High-efficiency motors cost roughly 20%–30% more than standard motors, but this expense is quickly repaid for motors that see continuous use.

Most efficient use of motors requires that attention be given to the following:

Optimum power—Motors operate most efficiently at rated voltage. Three-phase power supplies should be balanced; an unbalance of 3% can increase losses 25%.[1]

Good motor maintenance—Provide adequate cooling, keep heat transfer surfaces and vents clean, and provide adequate lubrication. Improved lubrication alone can increase efficiency a few percentage points.

Equipment scheduling—Turn equipment off when not in use; schedule large motor operation to minimize demand peaks.

Size equipment properly—Match the motor to the load and to the duty cycle. Motors operate most efficiently at rated load.

Evaluate continuous vs. batch processes—Sometimes a smaller motor operating continuously will be more economical.

Power factor—Correct if economics dictate savings. Motors have the best power factor at rated load.

Retrofit or new designs permit use of more efficient motors. For motors up to about 10–15 kW (15–20 hp) there are variations in efficiency. Select the most efficient motor for the job. Check to verify that the additional cost (if any) will be repaid by the savings that will accrue over the life of the installation.

In addition to reviewing the electric-drive system, consider the power train and the load. Friction results in energy dissipation in the form of heat. Bearings, gears, and belt drives all have certain losses, as do clutches. Proper operation and maintenance can reduce energy wastage in these systems and improve overall efficiency.

Material shaping and forming, such as is accomplished with machine tools, requires that electrical energy be transformed into various forms of mechanical energy. The energy expenditure related to the material and to the depth and speed of the cut. By experimenting with a specific process, it is possible to establish cutting rates that are optimum for the levels of production required and are most efficient in terms of energy use. Motors are not the only part of the electric-drive system that sustains losses. Other losses occur in the electric power systems that supply the motor. Electric power systems include substations, transformers, switching gear, distribution systems, feeders, power and lighting panels, and related equipment. Possibilities for energy management include the following:

Use highest voltages that are practical. For a given application, doubling the voltage cuts the required current in half and reduces the i^2r losses by a factor of four.

Eliminate unnecessary transformers. They waste energy. Proper selection of equipment and facility voltages can reduce the number of transformers required and cut transformer losses. Remember, the customer pays for losses when the transformers are on his side of the meter. For example, it is generally better to order equipment with motors of the correct voltage, even if this costs more, than to install special transformers.

Energy losses are an inherent part of electric power distribution systems. This is primarily due to i^2r losses and transformers. The end use conversion systems for electrical energy used in the process also contribute to energy waste. Proper design and operation of an electrical system can minimize energy losses and contribute to the reduction of electricity bills. Where long feeder runs are operated at near-maximum capacities, check to see if larger wire sizes would permit savings and be economically justifiable.

The overall power factor of electrical systems should be checked for low power factor. This could increase energy losses and the cost of electrical service, in addition to excessive voltage drops and increased penalty charges by the utility. Electrical systems studies should be made and consideration should be given to power factor correction capacitors. In certain applications as much as 10%–15% savings can be achieved in a poorly operating plant.

Check load factors. This is another parameter that measures the plant's ability to use electrical power efficiently. It is defined as the ratio of the actual kWh used to the maximum demand in kW times the total hours in the time period. A reduction in demand to bring this ratio closer to unity without decreasing plant output means more economical operation. For example, if the maximum demand for a given month (200 h) is 30,000 kWe and the actual kWh is 3.6×10^6 kWh, the load factor is 60%. Proper management of operations during high demand periods, which may extend only 15–20 min, can reduce the demand during that time without curtailing production. For example, if the 30,000 kWe could be reduced to 20,000 kWe, this would increase the load factor to about 90%. Such a reduction could amount to a \$20,000–\$50,000 reduction in the electricity bill.

Reduce peak loads wherever possible. Many nonessential loads can be shed during the demand peak without interrupting production. These loads would include such items as air compressors, heaters, coolers, and air conditioners. Manual monitoring and control is possible but is often impractical because of the short periods of time that are normally involved and the lack of centralized control systems. Automatic power demand control systems are available.

Provide improved monitoring or metering capability, submeters, or demand recorders. While it is true that meters alone will not save energy, plant managers need feedback to determine if their energy management programs are taking effect. Often the installation of meters on individual processes or buildings leads to immediate savings of 5%–10% by virtue of the ability to see how much energy is being used and to test the effectiveness of corrective measures.

10.4.3.3 Fans, Blowers, and Pumps

Simple control changes are the first thing to consider with these types of equipment. Switches, timeclocks, or other devices can insure that they do not operate except when needed by the process. Heat removal or process mass flow requirements will determine the size of fans and pumps. Often there is excess capacity, either as a result of design conservatism or because of process changes subsequent to the installation of equipment. The required capacity should be checked, since excess capacity leads to unnecessary demand charges and decreased efficiency.

For fans, the volume rate of airflow Q varies in proportion to the speed of the impeller:

$$Q = c_f N \quad \mathrm{m^3/s} \tag{10.14}$$

where Q = airflow in m^3/s; c_f = a constant with units m^3/r; and N = fan speed, r/s. The pressure developed by the fan varies as the square of the impeller speed. The important rule, however, is that the power needed to drive the fan varies as the cube of the speed:

$$P = P_c N^3 \ \mathrm{W} \tag{10.15}$$

where P = input power in watts and P_c = a constant with units W s^3/r^3.

The cubic law of pumping power indicates that if the airflow is to be doubled, eight (2^3) times as much power must be supplied. Conversely, if the airflow is to be cut in half, only one eighth ($1/2^3$) as much power must be supplied. Airflow (and hence power) can be reduced by changing pulleys or installing smaller motors.

Pumps follow laws similar to fans, the key being the cubic relationship of power to the volume pumped through a given system. Small decreases in flow rate, such as might be obtained with a smaller pump or gotten by trimming the impeller, can save significant amounts of energy.

Variable-speed drives (VSDs) are another technique for reducing process energy use. VSDs permit fans, blowers, and pumps to vary speed depending on process requirements. This can lead to significant savings on noncontinuous processes. Recent improvements in solid-state electronics have caused the price of VSDs to drop substantially. This is another technology that is supported by utility rebates in many areas.

10.4.3.4 Air Compressors

Compressed air is a major energy use in many manufacturing operations. Electricity used to compress air is converted into heat and potential energy in the compressed-air stream. Efficient operation of compressed-air systems therefore requires the recovery of excess heat where possible, as well as the maximum recovery of the stored potential energy.

Efficient operation is achieved in these ways:

Select the appropriate type and size of equipment for the duty cycle required. Process requirements vary, depending on flow rates, pressure, and demand of the system. Energy savings can be achieved by selecting the most appropriate equipment for the job. The rotary compressor is more popular for industrial operations in the range of 20–200 kW, even though it is somewhat less efficient than the reciprocal compressor. This has been due to lower initial cost and reduced maintenance. When operated at partial load, reciprocating units can be as much as 25% more efficient than rotary units. However, newer rotary units incorporate a valve that alters displacement under partial load conditions and improves efficiency. Selection of an air-cooled vs. a water-cooled unit would be influenced by whether water or air was the preferred medium for heat recovery.

Proper operation of compressed-air systems can also lead to improved energy utilization. Obviously, air leaks in lines and valves should be eliminated. The pressure of the compressed air should be reduced to a minimum. The percentage saving in power required to drive the compressor at a reduced pressure can be estimated from the fan laws described previously. For example, suppose the pressure were reduced to one-half the initial value. Since pressure varies as the square of the speed, this implies the speed would be 70.7% of the initial value. Since power varies as the cube of the speed, the power would now be $0.707^3 = 35\%$ of the initial value. Of course, this is the theoretical limit; actual compressors would not do as well, and the reduction would depend on the type of compressor. Measurements indicate that actual savings would be about half the theoretical limit; reducing pressure 50% would reduce brake horsepower about 30%. To illustrate this point further, for a compressor operating at 6.89×10^5 N/m^2 (100 psi) and a reduction of the discharge pressure to 6.20×10^5 N/m^2 (90 psi), a 5% decrease in brake horsepower would result. For a 373 kW (500 hp) motor operating for 1 year, the 150,000 kWh savings per year would result in about $9000 per year in electric power costs.

The intake line for the air compressor should be at the lowest temperature available. This normally means outside air. The reduced temperature of air intake results in a smaller volume of air to be compressed. The percentage horsepower saving relative to a 21°C (70°F) intake air temperature is about 2% for each 10°F drop in temperature. Conversely, input power increases by about 2% for each 10°F increase in intake air temperature.

Leakage is the greatest efficiency offender in compressed-air systems. The amount of leakage should be determined and measures taken to reduce it. If air leakage in a plant is more than 10% of the plant demand, a poor condition exists. The amount of leakage can be determined by a simple test during off-production hours (when air-using equipment is shut down) by noting the time that the compressor operates under load compared with the total cycle. This indicates the percentage of the compressor's capacity that is used to supply the plant air leakage. Thus if the load cycle compared with the total cycle were 60 s compared with 180 s, the efficiency would be 33%, or 33% of the compressor capacity is the amount of air leaking in m^3/min (ft.^{3}/min).

Recover heat where feasible. There are sometimes situations where water-cooled or air-cooled compressors are a convenient source of heat for hot water, space heating, or process applications. As a rough rule of thumb, about 300 J/m^3 min of air compressed ($\sim$10 Btu/ft.^{3} min) can be recovered from an air-cooled rotary compressor.

Substitute electric motors for air motor (pneumatic) drives. Electric motors are far more efficient. Typical vaned air motors range in size from 0.15 to 6.0 kW (0.2–8 hp), cost $300–$1500, and produce 1.4–27 N m (1–20 ft. lb) of torque at 620 kN/m^2 (90 psi) air pressure. These are used in manufacturing operations where electric motors would be hazardous, or where light weight and high power are essential. Inefficiency results from air system leaks and the need (compared to electric motors) to generate compressed air as an intermediate step in converting electric to mechanical energy.

Review air usage in paint spray booths. In paint spray booths and exhaust hoods, air is circulated through the hoods to control dangerous vapors. Makeup air is constantly required for dilution purposes. This represents a point of energy rejection through the exhaust air.

Examination should be made of the volumes of air required in an attempt in reduce flow and unnecessary operation. Possible mechanisms for heat recovery from the exhaust gases should be explored using recovery systems.

10.4.3.5 Electrochemical Operations

Electrochemical processes are an industrial use of electricity, particularly in the primary metals industry, where it is used in the extraction process for several important metals. Energy management opportunities include

Improve design and materials for electrodes. Evaluate loss mechanisms for the purpose of improving efficiency.

Examine electrolysis and plating operations for savings. Review rectifier performance, heat loss from tanks, and the condition of conductors and connections.

Welding is another electrochemical process. Alternating current welders are generally preferable when they can be used, since they have a better power factor, better demand characteristics, and more economical operation.

Welding operations can also be made more efficient by the use of automated systems which require 50% less energy than manual welding. Manual welders deposit a bead only 15%–30% of the time the machine is running. Automated processes, however, reduce the no-load time to 40% or less. Different welding processes should be compared in order to determine the most efficient process. Electroslag welding is suited only for metals over 1 cm (0.5 in.) thick but is more efficient than other processes.

Two other significant applications of electrolysis of concern to industry are batteries and corrosion. Batteries are used for standby power, transportation, and other applications. Proper battery maintenance, and improved battery design contribute to efficient energy use.

Corrosion is responsible for a large loss of energy-intensive metals every year and thus indirectly contributes to energy wastage. Corrosion can be prevented and important economies realized, by use of protective films, cathodic protection, and electroplating or anodizing.

10.4.3.6 Steam Systems

In as much as approximately 40% of the energy utilized in industry goes toward the production of process steam, it presents a large potential for energy misuse and fuel waste from improper maintenance and operation. Even though electrically generated steam and hot water is a small percentage of total industrial steam and hot water, the electrical fraction is likely to increase as other fuels increase in price. This makes increased efficiency even more important For example:

Steam leaks from lines and faulty valves result in considerable losses. These losses depend on the size of the opening and the pressure of the steam, but can be very costly. A hole 0.1 ft. in diameter with steam at 200 psig can bleed \$1000–\$2000 worth of steam (500 GJ) in a year.

Steam traps are major contributors to energy losses when not functioning properly. A large process industry might have thousands of steam traps, which could result in large costs if they are not operating correctly. Steam traps are intended to remove condensate and noncondensable gases while trapping or preventing the loss of steam. If they stick open, orifices as large as 6 mm (0.25 in.) can allow steam to escape. Such a trap would allow 1894 GJ/year (2000 MBtu/year) of heat to be rejected to the atmosphere on a 6.89×10^5 N/m (100 psi) pressure steam line. Many steam traps are improperly sized, contributing to an inefficient operation. Routine inspection, testing, and a correction program for steam valves and traps are essential in any energy program and can contribute to cost savings.

Poor practice and design of steam distribution systems can be the source of heat waste up to 10% or more. It is not uncommon to find an efficient boiler or process plant joined to an inadequate steam distribution system. Modernization of plants results from modified steam requirements. The old distribution systems are still intact, however, and can be the source of major heat losses. Large steam lines intended to supply units no longer present in the plant are sometimes used for minor needs, such as space heating and cleaning operations, that would be better accomplished with other heat sources.

Steam distribution systems operating on an intermittent basis require a start-up warming time to bring the distribution system into proper operation. This can extend up to 2 or 3 h, which puts a demand on fuel needs. Not allowing for proper ventilating of air can also extend the start-up time. In addition, condensate return can be facilitated if it is allowed to drain by gravity into a tank or receiver and is then pumped into the boiler feed tank.

Proper management of condensate return. Proper management can lead to great savings. Lost feedwater must be made up and heated. For example, every 0.45 kg (1 lb) of steam that must be generated from 15°C feedwater instead of 70°C feedwater requires an additional 1.056×10^5 J (100 Btu) more than 1.12 MJ (1063 Btu) required or a 10% increase in fuel. A rule of thumb is that a 1% fuel saving results for every 5°C increase in feedwater temperature. Maximizing condensate recovery is an important fuel laying procedure.

Poorly insulated lines and valves due either to poor initial design or a deteriorated condition. Heat losses from a poorly insulated pipe can be costly. A poorly insulated line carrying steam at 400 psig can lose ~1000 GJ/year (10^9 Btu/year) or more per 30 m (100 ft.) of pipe. At steam costs of $2.00/GJ, this translates to a $2000 expense per year.

Improper operation and maintenance of tracing systems. Steam tracing is used to protect piping and equipment from cold weather freezing. The proper operation and maintenance of tracing systems will not only insure the protection of traced piping but also saves fuel. Occasionally these systems are operating when not required. Steam is often used in tracing systems and many of the deficiencies mentioned earlier apply (e.g., poorly operating valves, insulation, leaks).

Reduce losses in process hot water systems. Electrically heated hot water systems are used in many industrial processes for cleaning, pickling, coating, or etching components. Hot or cold water systems can dissipate energy. Leaks and poor insulation should be repaired.

10.4.3.7 Electrical Process Heat

Industrial process heat applications can be divided into four categories: direct-fired, indirect-fired, fuel, or electric. Here we shall consider electric direct-fired installations (ovens, furnaces) and indirect-fired (electric water heaters and boilers) applications. Electrical installations use metal sheath resistance heaters, resistance ovens or furnaces, electric salt bath furnaces, infrared heaters, induction and high-frequency resistance heaters, dielectric heaters, and direct arc furnaces. From the housekeeping and maintenance point of view, typical opportunities would include:

Repair or improve insulation. Operational and standby losses can be considerable, especially in larger units. Remember that insulation may degrade with time or may have been optimized to different economic criteria.

Provide finer controls. Excessive temperatures in process equipment waste energy. Run tests to determine the minimum temperatures that are acceptable, then test instrumentation to verify that it can provide accurate process control and regulation.

Practice heat recovery. This is an important method, applicable to many industrial processes as well as HVAC systems and so forth. It is described in more detail in the next section.

10.4.3.8 Heat Recovery

Exhaust gases from electric ovens and furnaces provide excellent opportunities for heat recovery. Depending on the exhaust-gas temperature, exhaust heat can be used to raise steam or to preheat air or feedstocks. Another potential source of waste-heat recovery is the exhaust air that must be rejected from industrial operations in order to maintain health and ventilation safety standards. If the reject air has been subjected to heating and cooling processes, it represents an energy loss inasmuch as the makeup air must be modified to meet the interior conditions. One way to reduce this waste is through the use of heat wheels or similar heat exchange systems.

Energy in the form of heat is available at a variety of sources in industrial operations, many of which are not normally derived from primary heat sources. Such sources include electric motors, crushing and grinding operations, air compressors, and drying processes. These units require cooling in order to maintain proper operation. The heat from these systems can be collected and transferred to some appropriate use such as space heating or water heating.

The heat pipe is gaining wider acceptance for specialized and demanding heat transfer applications. The transfer of energy between incoming and outgoing air can be accomplished by banks of these devices. A refrigerant and a capillary wick are permanently sealed inside a metal tube, setting up a liquid-to-vapor circulation path. Thermal energy applied to either end of the pipe causes the refrigerant to vaporize. The refrigerant vapor then travels to the other end of the pipe, where thermal energy is removed. This causes the vapor to condense into liquid again, and the condensed liquid then flows back to the opposite end through the capillary wick.

Industrial operations involving fluid flow systems that transport heat such as in chemical and refinery operations offer many opportunities for heat recovery. With proper design and sequencing of heat exchangers, the incoming product can be heated with various process steams. For example, proper heat exchanger sequence in preheating the feedstock to a distillation column can reduce the energy utilized in the process.

Many process and air-conditioning systems reject heat to the atmosphere by means of wet cooling towers. Poor operation can contribute to increased power requirements.

Water flow and airflow should be examined to see that they are not excessive. The cooling tower outlet temperature is fixed by atmospheric conditions if operating at design capacity. Increasing the water flow rate or the airflow will not lower the outlet temperature.

The possibility of utilizing heat that is rejected to the cooling tower for other purposes should be investigated. This includes preheating feedwater, heating hot water systems, space heating and other low-temperature applications. If there is a source of building exhaust air with a lower wet bulb temperature, it may be efficient to supply this to a cooling tower.

10.4.3.9 Power Recovery

Power recovery concepts are an extension of the heat recovery concept described earlier. Many industrial processes have pressurized liquid and gaseous streams at 150°C–375°C (300°F–700°F) that present excellent opportunities for power recovery. In many cases high-pressure process stream energy is lost by throttling across a control valve.

The extraction of work from high-pressure liquid streams can be accomplished by means of hydraulic turbines (essentially diffuser-type or volute-type pumps running backward). These pumps can be either single or multistage. Power recovery ranges from 170 to 1340 kW (230–1800 hp). The lower limit of power recovery approaches the minimum economically justified for capital expenditures at present power costs.

10.4.3.10 Heating, Ventilating, and Air-Conditioning Operation

The environmental needs in an industrial operation can be quite different from those in a residential or commercial structure. In some cases strict environmental standards must be met for a specific function or process. More often the environmental requirements for the process itself are not severe; however, conditioning of the space is necessary for the comfort of operating personnel, and thus large volumes of air must be processed. Quite often opportunities exist in the industrial operation where surplus energy can be utilized in environmental conditioning. A few suggestions follow:

Review HVAC controls. Building heating and cooling controls should be examined and preset.

Ventilation, air, and building exhaust requirements should be examined. A reduction of airflow will result in a savings of electrical energy delivered to motor drives and additionally reduce the energy requirements for space heating and cooling. Because pumping power varies as the cube of the airflow rate, substantial savings can be achieved by reducing airflows where possible.

Do not condition spaces needlessly. Review air-conditioning and heating operations, seal off sections of plant operations that do not require environmental conditioning, and use air-conditioning equipment only when needed. During nonworking hours the environmental control equipment should be shut down or reduced. Automatic timers can be effective.

Provide proper equipment maintenance. Insure that all equipment is operating efficiently. (Filters, fan belts, and bearings should be in good condition.)

Use only equipment capacity needed. When multiple units are available, examine the operating efficiency of each unit and put operations in sequence in order to maximize overall efficiency.

Recirculate conditioned (heated or cooled) air where feasible. If this cannot be done, perhaps exhaust air can be used as supply air to certain processes (e.g., a paint spraybooth) to reduce the volume of air that must be conditioned.

For additional energy management opportunities in HVAC systems, see Chapter 6.

10.4.3.11 Lighting

Industrial lighting needs range from low-level requirements for assembly and welding of large structures (such as shipyards) to the high levels needed for manufacture of precision mechanical and electronic components (e.g., integrated circuits). There are four basic housekeeping checks that should be made:

Is a more efficient lighting application possible? Remove excessive or unnecessary lamps.

Is relamping possible? Install lower-wattage lamps during routine maintenance.

Will cleaning improve light output? Fixtures, lamps, and lenses should be cleansed periodically.

Can better controls be devised? Eliminate turning on more lamps than necessary. For modification, retrofit, or new design, consideration should be given to the spectrum of high-efficiency lamps and luminaires that are available. For example, high-pressure sodium lamps are finding increasing acceptance for industrial use, with savings of nearly a factor of five compared to incandescent lamps. See Chapter 5 for additional details.

10.4.3.12 The New Electrotechnologies

Electricity has certain characteristics that make it uniquely suitable for industrial processes. These characteristics include electricity's suitability for timely and precise control; its ability to interact with materials at the molecular level; the ability to apply it selectively and specifically, and the ability to vary its frequency and wavelength so as to enhance or inhibit its interaction with materials. These aspects may be said to relate to the *quality* of electricity as an energy form. It is important to recognize that different forms of energy have different qualities in the sense of their ability to perform useful work. Thus, although the Btu content of two energy forms may be the same, their ability to transform materials may be quite different

New electrotechnologies based on the properties of electricity are now finding their way into modern manufacturing. In many cases the introduction of electricity reduces manufacturing costs, improves quality reduces pollution, or has other beneficial results. Some examples include

- Microwave heating
- Induction heating
- Plasma processing
- Magnetic forming
- RF drying and heating
- Ion nitriding
- Infrared drying
- UV drying and curing
- Advanced finishes
- Electron beam heating

Microwave heating is a familiar technology that exhibits the unique characteristics of electricity described earlier. First it is useful to review how conventional heating is preformed to dry paint, anneal a part, or remove water. A source of heat is required, along with a container (oven, furnace, pot, etc.) to which the heat is applied. Heat is transferred from the container to the work piece by conduction, radiation, convection, or a combination of these. There are certain irreversible losses associated with heat transfer in this process. Moreover, since the container must be heated, more energy is expended than is really required. Microwave heating avoids these losses due to the unique characteristics of electricity.

Timely control. There is no loss associated with the warmup or cooldown of ovens. The heat is applied directly when needed.

Molecular interaction. By interacting at the molecular level, heat is deposited directly in the material to be heated, without having to preheat an oven, saving the extra energy required for this purpose and avoiding the losses that result from heat leakage from the oven.

Selective application. By selectively applying heat only to the material to be heated, parasitic losses are avoided. In fact, the specificity of heat applied this way can improve quality by not heating other materials.

Selective wavelength and frequency. A microwave frequency is selected that permits the microwave energy to interact with the material to be heated, and not with other materials. Typically the frequency is greater than 2000 MHz.

Microwave heating was selected for this discussion, but similar comments could be made about infrared, ultraviolet (UV), dielectric, induction, or electron beam heating. In each case the frequency or other characteristics of the energy form are selected to provide the unique performance required.

Ultraviolet curing (now used for adhesive and finishes) is another example. The parts to be joined or coated can be prepared and the excessive adhesive removed without fear of prehardening. Then the UV energy is applied, causing the adhesive to harden.

Induction heating is another example. It is similar to microwave heating except that the energy is applied at a lower frequency. Induction heating operates on the principal of inducing electric currents to flow in materials, heating them by the power dissipated in the material. The method has several other advantages. In a conventional furnace, the work piece has to be in the furnace for a sufficient time to reach temperature. Because of this, some of the material is oxidized and lost as scale. In a typical high-temperature gas furnace this can be 2% of the throughput. Additional product is scrapped as a result of surface defects caused by uneven heating and cooling. This can amount to another 1% of throughput. Induction heating can reduce these losses by a factor of four.

The fact that electricity can be readily controlled and carries with it a high information content through digitization or frequency modulation also offers the potential for quantum improvements in efficiency. A slightly different example is the printing industry.

Today the old linotype technology has been replaced by electronic processes. The lead melting pots that used to operate continuously in every newspaper plant have been removed, eliminating a major energy use and an environmental hazard. Books, magazines, and newspapers can be written composed, and printed entirely by electronic means. Text is processed by computer techniques. Camera-ready art is prepared by computers directly or prepared photographically and then optically scanned to create digital images. The resulting electronic files can be used in web offset printing by an electronic photochemical process. The same information can be transmitted electronically; via satellite, to a receiving station at a remote location where a high-resolution fax machine reconstitutes the image. This method is being used to simultaneously and instantaneously distribute advertising copy to multiple newspapers, using a single original. Previously, to insert an advertisement in 25 newspapers, 25 sets of photographic originals would have to be prepared and delivered, by messenger, air express, or mail, to each newspaper.

Some of the other applications of the new electrotechnologies include RF drying of plywood veneers, textiles, and other materials; electric infrared drying for automobile paint and other finishes; electric resistance melting for high purity metals and scrap recovery; and laser cutting of wood, cloth, and other materials.

10.4.3.13 General Industrial Processes

The variety of industrial processes is so great that detailed specific recommendations are outside the scope of this chapter. Useful sources of information are found in trade journals, vendor technical bulletins, and manufacturers' association journals. These suggestions are intended to be representative, but by no means do they cover all possibilities.

In machining operations, eliminate unnecessary operations and reduce scrap. This is so fundamental from a purely economic point of view that it will not be possible to find significant improvements in many situations. The point is that each additional operation and each increment of scrap also represents a needless use of energy. Machining itself is not particularly energy-intensive. Even so, there are alternate technologies that can not only save energy but reduce material wastage as well. For example, powder metallurgy generates less scrap and is efficient if done in induction-type furnaces.

Use stretch forming. Forming operations are more efficient if stretch forming is used. In this process sheet metal or extrusions are stretched 2%–3% prior to forming, which makes the material more ductile so that less energy is required to form the product. The finished part

Use alternate heat treating methods. Conventional heat treating methods such as carburizing are energy-intensive. Alternate approaches are possible. For example, a hard surface can be produced by induction heating, which is a more efficient energy process. Plating, metallizing, flame spraying, or cladding can substitute for carburizing, although they do not duplicate the fatigue strengthening compressive skin of carburization or induction hardening.

Use alternative painting methods. Conventional techniques using solvent-based paints require drying and curing at elevated temperature. Powder coating is a substitute process in which no solvents are used. Powder particles are electrostatically charged and attracted to the part being painted so that only a small amount of paint leaving the spray gun misses the part and the overspray is recoverable. The parts can be cured rapidly in infrared ovens, which require less energy than standard hot air systems. Water-based paints and high-solid coatings are also being used and are less costly than solvent-based paints. They use essentially the same equipment as the conventional solvent paint spray systems so that the conversion can be made at minimum costs. New water-based emulsion paints contain only 5% organic solvent and require no afterburning. High-solids coatings are already in use commercially for shelves, household fixtures, furniture, and beverage cans, and require no afterburning. They can be as durable as conventional finishes and are cured by either conventional baking or UV exposure.

Substitute for energy-intensive processes such as hot forging. Hot forging may require a part to go through several heat treatments. Cold forging with easily wrought alloys may offer a replacement. Lowering the preheat temperatures may also be an opportunity for savings. Squeeze forging is a relatively new process in which molten metal is poured into the forging dye. The process is nearly scrap free, requires less press power, and promises to contribute to more efficient energy utilization.

Movement of materials through the plant creates opportunities for saving energy. Material transport energy can be reduced by

Combining processes or relocate machinery to reduce transport energy. Sometimes merely relocating equipment can reduce the need to haul materials.

Turning off conveyors and other transport equipment when not needed. Look for opportunities where controls can be modified to permit shutting down of equipment not in use.

Using gravity feeds wherever possible. Avoid unnecessary lifting and lowering of products.

10.4.3.14 Demand Management

The cost of electrical energy for medium to large industrial and commercial customers generally consists of two components. One component is the *energy charge*, which is based on the cost of fuel to the utility, the average cost of amortizing the utility generating plant, and on the operating and maintenance costs experienced by the utility. Energy costs for industrial users in the United States are typically in the range of 0.05–0.10 $/kWh.

The second component in the *demand charge*, which reflects the investment cost the utility must make to serve the customer. Besides the installed generating capacity needed, the utility also provides distribution lines, transformers, substations, and switches whose cost depends on the size of the load being served. This cost is recovered in a demand charge which typically is 2–10 $/kW month.

Demand charges typically account for 10%–50% of the bill, although wide variations are possible depending on the type of installation. Arc welders, for example, have relatively high demand charges, since the installed capacity is great (10–30 kW for a typical industrial machine) and the energy use is low.

From the utility's point of view it is advantageous to have its installed generating capacity operating at full load as much of the time as possible. To follow load variations conveniently, the utility operates its largest and most economical generating units continuously to meet its base load, and then brings smaller (and generally more expensive) generating units on line to meet peak load needs.

Today consideration is being given to time-of-day or *peak load pricing* as a means of assigning the cost of operating peak generating capacity to those loads that require it. From the viewpoint of the utility, *load management* implies maintaining a high-capacity factor and minimizing peak load demands. From the customer's viewpoint, *demand management* means minimizing electrical demands (both on- and off-peaks) so as to minimize overall electricity costs.

Utilities are experimenting with several techniques for load management. Besides rate schedules that encourage the most effective use of power, some utilities have installed remotely operated switches that permit the utility to disconnect nonessential parts of the customer's load when demand is excessive. These switches are actuated by a radio signal, through the telephone lines, of over the power grid itself through a harmonic signal (ripple frequency) that is introduced into the grid.

Customers can control the demand of their loads by any of several methods:

- Manually switching off loads ("load shedding")
- Use of timers and interlocks to prevent several large loads from operating simultaneously
- Use of controllers and computers to control loads and minimize peak demand by scheduling equipment operation
- Energy storage (e.g., producing hot or chilled water during off-peak hours and storing it for use on-peak)

Demand can be monitored manually (by reading a meter) or automatically using utility-installed equipment or customer-owned equipment installed in parallel with the utility meter. For automatic monitoring, the basic approach involves pulse counting.

The demand meter produces electronic pulses, the number of which is proportional to demand n kW. Demand is usually averaged over some interval (e.g., 15 min) for calculating cost. By monitoring the pulse rate electronically, a computer can project what the demand will be during the next demand measurement interval, and can then follow a preestablished plan for shedding loads if the demand set point is likely to be exceeded.

Computer control can assist in the dispatching of power supply to the fluctuating demands of plant facilities. Large, electrically-based facilities are capable of forcing large power demands during peak times that exceed the limits contracted with the utility or cause penalties in increased costs. Computer control can even out the load by shaving peaks and filling in the valleys, thus minimizing power costs. In times of emergency or fuel curtailment, operation of the plant can be programmed to provide optimum production and operating performance under prevailing conditions. Furthermore, computer monitoring and control provide accurate and continuous records of plant performance.

It should be stressed here that many of these same functions can be carried out by manual controls, time clocks, microprocessors, or other inexpensive devices. Selection of a computer system must be justified economically on the basis of the number of parameters to be controlled and the level of sophistication required. Many of the benefits described here can be obtained in some types of operations without the expense of a computer.

10.5 Thermal Energy Management in Industry

10.5.1 The Importance of Fuel Use and Heat in Industry

The U.S. manufacturing sector depends heavily on fuels for the conversion of raw materials into usable products. Industry uses a wide range of fuels, including natural gas, petroleum, coal, and renewables. The petroleum forms used include distillate fuel oil, residual fuel oil, gasoline, LPG, and others. How efficiently energy is used, its cost, and its availability consequently have a substantial impact on the competitiveness and economic health of U.S. manufacturers. More efficient use of fuels lowers production costs, conserves limited energy resources, and increases productivity. Efficient use of energy also has positive impacts on the environment—reductions in fuel use translate directly into decreased emissions of pollutants such as sulfur oxides, nitrogen oxides, particulates, and greenhouse gases (e.g., carbon dioxide).

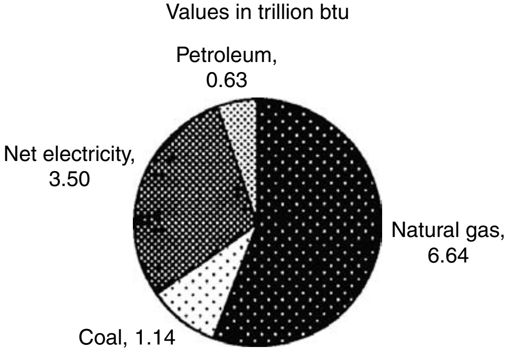

FIGURE 10.10 Manufacturing energy consumption by fuel (end use data). (From Manufacturing Energy Consumption Survey, 1998; U.S. Department of Energy; Energy Information Agency, 2002.)

From Figure 10.10, it can be seen that fuel use in manufacturing is just over 70% of the total energy used in manufacturing on an end use basis. Figure 10.11 shows the percentage of each fuel used for boiler fuel and process heat combined. Of this total, 53% is used for boiler fuel, and 47% for direct process heating. Thus, there is a huge potential for energy management and energy-efficiency improvement related to the use fuels and thermal energy in industry. Section 10.5 discusses the use of improved and new equipment and technology to accomplish some of these reductions in energy use and cost.

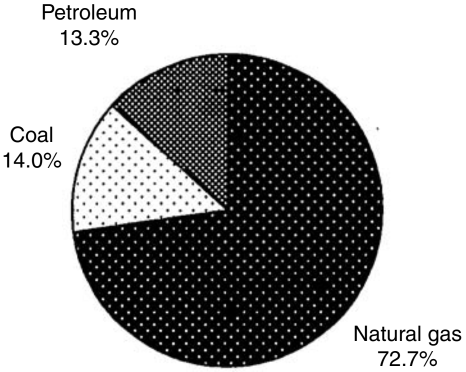

FIGURE 10.11 Manufacturing energy use for boiler fuel and process heating end use basis. (From Manufacturing Energy Consumption Survey, 1998; U.S. Department of Energy; Energy Information Agency, 2002.)

Energy efficiency can be defined as the effectiveness with which energy resources are converted into usable work. Thermal efficiency is commonly used to measure the efficiency of energy conversion systems such as process heaters, steam systems, engines, and power generators. Thermal efficiency is essentially the measure of the efficiency and completeness of fuel combustion, or, in more technical terms, the ratio of the net work supplied to the heat supplied by the combusted fuel. In a gas-fired heater, for example, thermal efficiency is equal to the total heat absorbed divided by the total heat supplied; in an automotive engine, thermal efficiency is the work done by the gases in the cylinder divided by the heat energy of the fuel supplied.[1]

Energy efficiency varies dramatically across industries and manufacturing processes, and even between plants manufacturing the same products. Efficiency can be limited by mechanical, chemical, or other physical parameters, or by the age and design of equipment. In some cases, operating and maintenance practices contribute to lower-than-optimum efficiency. Regardless of the reason, less-than-optimum energy efficiency implies that not all of the energy input is being converted to useful work—some is released as lost energy. In the manufacturing sector, these energy losses amount to several quadrillion BTUs (quadrillion British thermal units, or quads) and billions of dollars in lost revenues every year.

Typical thermal efficiencies of selected energy systems and industrial equipment[25] is provided in the following table:

Power generation	25%–44%
Steam boilers (natural gas)	80%
Steam boilers (coal and oil)	84%–85%
Waste-heat boilers	60%–70%
Thermal cracking (refineries)	58%–61%
EAF steelmaking	56%
Paper drying	48%
Kraft pulping	60%–69%
Distillation column	25%–40%
Cement calciner	30%–70%
Compressors	10%–20%
Pumps and fans	55%–65%
Motors	90%–95%

Boiler losses represent energy lost due to boiler inefficiency. In practice, boiler efficiency can be as low as 55%–60%, or as high as 90%. The age of the boiler, maintenance practices, and fuel type are contributing factors to boiler efficiency. It is assumed that the greater losses are in steam pipes (20%), with small losses incurred in other fuel transmission lines (3%) and electricity transmission lines (3%). Losses in steam pipes and traps have been reported to be as high as from 20%–40%. A conservative value of 20% was used for steam distribution losses in this study.[1]

10.5.2 Boiler Combustion Efficiency Improvement

Boilers and other fuel-fired equipment, such as ovens and kilns, combust fuel with air for the purpose of releasing chemical energy as heat. For an industrial boiler, the purpose is to generate high-temperature and high-pressure steam to use directly in a manufacturing process, or to operate other equipment such as steam turbines to produce shaft power. As shown earlier in Figure 10.11, the predominant boiler fuel is natural gas. The efficiency of any combustion process is dependent on the amount of air that is used in relation to the amount of fuel and how they are mixed. Air is about 20% oxygen, so approximately five units of air must be brought in to the boiler for every one unit of oxygen that is needed. Controlling this air–fuel mixture, and minimizing the amount of excess air while still obtaining safe mixing of the air and fuel, is key to insuring a high combustion efficiency in the boiler.[26]

10.5.2.1 Combustion Control

The stoichiometric equation for the combustion of methane, the principal constituent of natural gas, with air is

$$CH_4 + 2O_2 + 7.52N_2 \rightarrow CO_2 + 2H_2O + 7.52N_2 \tag{10.16}$$

The stoichiometric equation is the one representing the exact amount of air necessary to oxidize the carbon and hydrogen in the fuel to carbon dioxide and water vapor. However, it is necessary to provide more than the stoichiometric amount of air since the mixing of fuel and air is imperfect in the real combustion chamber. Thus the combustion equation for hydrocarbon fuels becomes

$$\begin{aligned} C_xH_y + \phi(x+y/4)O_2 + 3.76\phi(x+y/4)N_2 &\rightarrow xCO_2 + y/2H_2O \\ &+ (\phi-1)(x+y/4)O_2 + 3.76\phi(x+y/4)N_2 \end{aligned} \tag{10.17}$$

Note that for a given fuel nothing in the equation changes except the parameter ϕ, the equivalence ratio, as the fuel–air ratio changes.

As ϕ is increased beyond the optimal value for good combustion, the stack losses increase and the heat available for the process decreases. As the equivalence ratio increases for a given flue temperature and a given fuel, more fuel must be consumed to supply a given amount of heat to the process.

The control problem for the furnace or boiler is to provide the minimum amount of air for good combustion over a wide range of firing conditions and a wide range of ambient temperatures. The most common combustion controller uses the ratio of the pressure drops across orifices, nozzles, or Venturis in the air and fuel lines. Since these meters measure volume flow, a change in temperature of combustion air with respect to fuel, or vice versa, will affect the equivalence ratio of the burner. Furthermore, since the pressure drops across the flow meters are exponentially related to the volume flow rates control dampers must have very complicated actuator motions. All the problems of ratio controllers are eliminated if the air is controlled from an oxygen meter. These are now coming into more general use as reasonably priced, high-temperature oxygen sensors become available. It is possible to control to any set value of percentage oxygen in the products; that is,

$$\%\ O_2 = \frac{\phi - 1}{\frac{x+y/2}{x+y/4} + 4.76\ \phi - 1} \tag{10.18}$$

Figure 10.12 is a nomograph from the Bailey Meter Company (Dukelow, 1974) that gives estimates of the annual dollar savings resulting from the reduction of excess air to 15% for gas-, oil-, or coal-fired boilers with stack temperatures from 300°F to 700°F. The fuel savings are predicted on the basis that as excess air is reduced, the resulting reduction in mass flow of combustion gases results in reduced gas velocity and thus a longer gas residence time in the boiler. The increased residence time increases the heat transfer from the gases to the water. The combined effect of lower exhaust-gas flows and increased heat exchange effectiveness is estimated to be 1.5 times greater than that due to the reduced mass flow alone.

As an example assume the following data pertaining to an oil-fired boiler. Entering the graph at the top abscissa with 6.2% O_2, we drop to the oil fuel line and then horizontally to the 327°C (620°F) flue gas temperature line. Continuing to the left ordinate we can see that 6.2% O_2 corresponds to 37.5% excess air. Dropping vertically from the intersection of the flue gas temperature line and the excess air line we note a 3.4% total fuel savings. Fuel costs are

Burner capacity	63 GJ/hr (60×10^6 Btu/hr)
Annual operating hours	6,200
Fuel cost	\$0.38/L (\$1.44/gal)
Heating value fuel	42.36 MJ/L (152,000 Btu/gal)
Percent O_2 in exhaust gases	6.2%
Stack temperature	327°C (620°F)

$$10^9\text{J/GJ}(10^6\text{Btu/million Btu}) \times \frac{\$0.38/\text{L}}{42,365,00\text{J/L}}\left(\frac{\$1.44/\text{gal}}{152,000\ \text{Btu/gal}}\right) = \$8.96/\text{GJ}(\$9.48/\text{million Btu})$$

Continuing the vertical line to intersect the \$2.50/million Btu and then moving to left ordinate shows a savings of \$140,000 per year for 8000 h of operation, 100×10^6 Btu/hr input and \$5.00/million Btu fuel

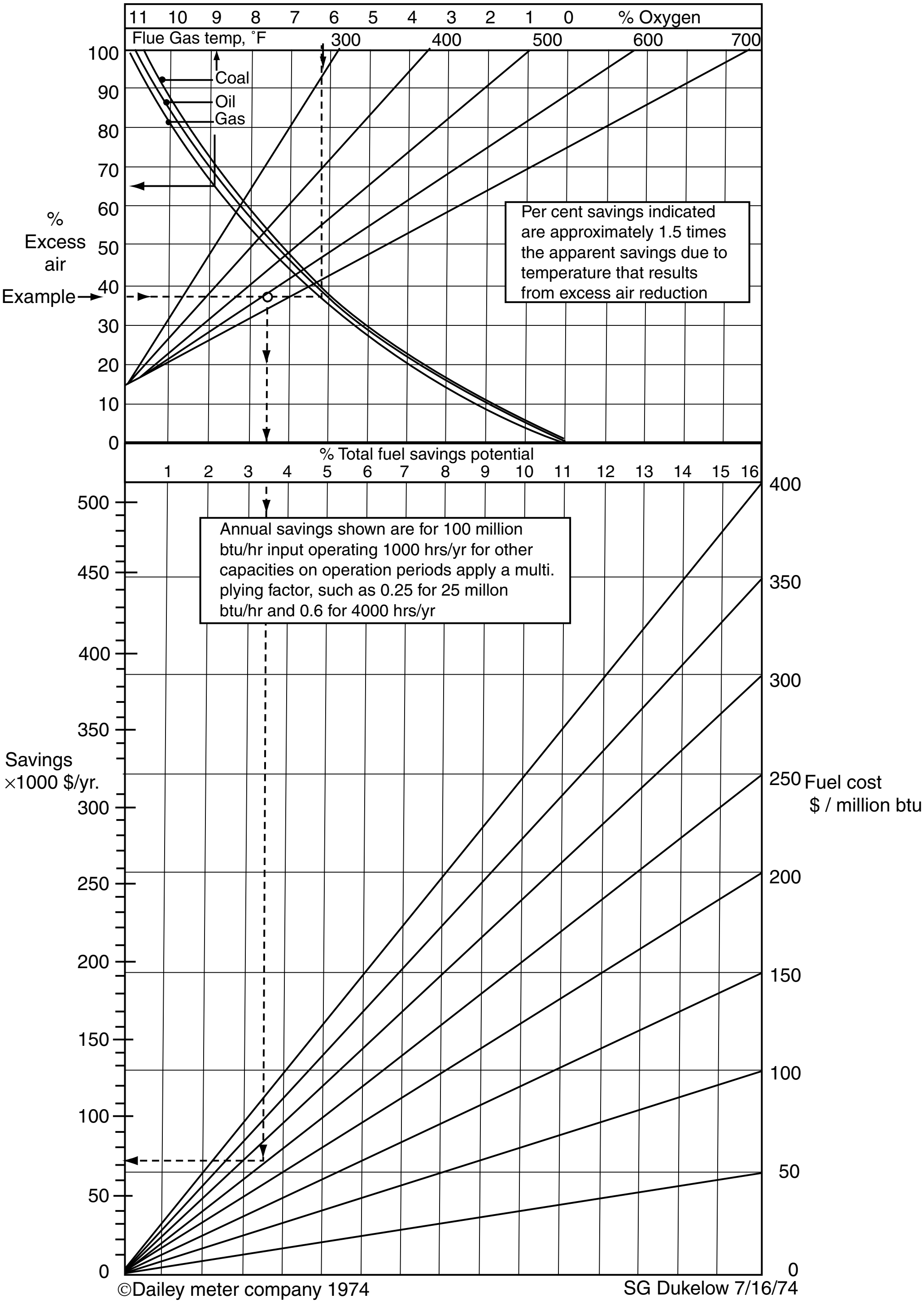

FIGURE 10.12 Nomograph for estimating savings from adjustment of burners. (From Dukelow, S. G., Bailey Meter Company, 29801 Euclid Avenue, Wickliffe, Ohio, 1974. With permission.)

cost. Adjusting that result for the assumed operating data:

$$\text{Annual savings} = \frac{6,200}{8,000} \times \frac{60 \times 10^6}{100 \times 10^6} \times \frac{9.48}{5.00} \times \ \$140,000 = \ \$123,430 \text{ per year}$$

This savings could be obtained by installing a modern oxygen controller, an investment with approximately a 1-year payoff, or from heightened operator attention with frequent flue gas testing and manual adjustments. Valuable sources of information concerning fuel conservation in boilers and furnaces are given by the DOE/OIT website.

10.5.2.2 Waste-Heat Management

Waste heat as generally understood in industry is the energy rejected from any process to the atmospheric air or to a body of water. It may be transmitted by radiation, conduction, or convection, but often it is contained in gaseous or liquid streams emitted to the environment. Almost 50% of all fuel energy used in the United States is transferred as waste heat to the environment, causing thermal pollution as well as chemical pollution of one sort or another. It has been estimated that half of that total may be economically recoverable for useful heating functions.

What must be known about waste-heat streams in order to decide whether they can become useful? Here is a list along with a parallel list of characteristics of the heat load that should be matched by the waste-heat supply.

Waste-Heat Supply
Quantity
Quality
Temporal availability of supply
Characteristics of fluid

Heat Load
Quantity required
Quality required
Temporal availability of load
Special fluid requirements

Let us examine the particular case of a plant producing ice-cream cones. All energy quantities are given in terms of 15.5°C reference temperature. Sources of waste heat include

- Products of combustion from 120 natural gas jets used to heat the molds in the carousel-type baking machines. The stack gases are collected under an insulated hood and released to the atmosphere through a short stack. Each of six machines emits 236.2 m^3/hr of stack gas at 160°C. Total source rate is 161,400 kJ/hr or 3874 MJ/day for a three-shift day.
- Cooling water from the jackets, intercoolers, and aftercoolers of two air compressors used to supply air to the pneumatic actuators of the cone machines; 11.36 L/min of water at 48.9°C is available. This represents a source rate of 96 MJ/hr. The compressors run an average of 21 h per production day. Thus this source rate is 2015 MJ/day.
- The water chillers used to refrigerate the cone batter make available—at 130°F—264 MJ/hr of water heat. This source is available to heat water to 48.9°C using desuperheaters following the water chiller compressors. The source rate is 6330 MJ/day.
- 226 m^3/min of ventilating air is discharged to the atmosphere at 21.2°C. This is a source of rate of less than 22.2 MJ/hr or 525 MJ/day.

Uses for waste heat include

- 681 L/hr of hot water at 82.2°C is needed for cleanup operations during 3 h of every shift or during 9 of every 24 h. Total daily heat load is 4518 MJ.

- Heating degree-days total in excess of 3333 annually. Thus any heat available at temperatures above 21.1°C can be utilized with the aid of runaround systems during the 5(1/2)-month heating season. Estimated heating load per year is 4010 GJ.
- Total daily waste heat available—12.74 GJ/day
- Total annual waste heat available—3.19 TJ/year
- Total annual worth of waste heat (at $5.00/GJ for gas)—$15,893
- Total daily heat load—this varies from a maximum of 59.45 GJ/day at the height of the heating season to the hot-water load of 4.52 GJ/day in the summer months.

Although the amount of waste heat from the water chillers is 40% greater than the load needed for hot-water heating, the quality is insufficient to allow its full use, since the hot water must be heated to 82°C and the compressor discharge is at a temperature of 54°C.

However the chiller waste heat can be used to preheat the hot water. Assuming 13°C supply water and a 10° heat exchange temperature approach, the load that can be supplied by the chiller is

$$\frac{49-13}{82-13} \times 4.52 = 2.36\ \text{GJ/day}$$

Since the cone machines have an exhaust-gas discharge of 3.87 GJ/day at 160°C, the remainder of the hot-water heating load of 2.17 GJ/day is available. Thus a total saving of 1129 GJ/year in fuel is possible with a cost saving of $5645 annually based on $5.00/GJ gas. The investment costs will involve the construction of a common exhaust heater for the cone machines, a desuperheater for each of the three water chiller compressors, a gas-to-liquid heat exchanger following the cone-machine exhaust heater, and possibly an induced draft fan following the heat exchanger, since the drop in exhaust-gas temperature will decrease the natural draft due to hot-gas buoyancy.

It is necessary to almost match four of four characteristics. Not exactly, of course, but the closer means thermodynamic availability of the waste heat. Unless the energy of the waste stream is sufficiently hot, it will be impossible to even transfer it to the heat load, since spontaneous heat transfer occurs only from higher to lower temperature.

The quantity and quality of energy available from a waste-heat source or for a heat load are studied with the aid of a heat balance. Figure 10.13 shows the heat balance for a steam boiler. The rates of enthalpy entering or leaving the system fluid streams must balance with the radiation loss rate from the boiler's external surfaces. Writing the First-Law equation for a steady-flow-steady-state process

$$\dot{q}_{\mathrm{L}} = \dot{m}_{\mathrm{f}} h_{\mathrm{f}} + \dot{m}_{\mathrm{a}} h_{\mathrm{a}} + \dot{m}_{\mathrm{c}} h_{\mathrm{c}} - \dot{m}_{\mathrm{s}} h_{\mathrm{s}} - \dot{m}_{\mathrm{g}} h_{\mathrm{g}} \tag{10.19}$$

and referring to the heat-balance diagram, one sees that the enthalpy flux $\dot{m}_{\mathrm{g}} h_{\mathrm{g}}$, leaving the boiler in the exhaust-gas stream, is a possible source of waste heat. A fraction of that energy can be transferred in a heat exchanger to the combustion air, thus increasing the enthalpy flux $\dot{m}_{\mathrm{g}} h_{\mathrm{a}}$ and reducing the amount of fuel required. The fraction of fuel that can be saved is given in the equation

$$\frac{\dot{m}_{\mathrm{f}} - \dot{m}_{\mathrm{f}'}}{\dot{m}_{\mathrm{f}}} = 1 - \left[\frac{K_1 - (1+\phi)\bar{C}_{\mathrm{p}} T_{\mathrm{g}}}{K_1 - (1+\phi')\bar{C}'_{\mathrm{p}} T'_{\mathrm{g}}}\right] \tag{10.20}$$

where the primed values are those obtained with waste-heat recovery. K_1 represents the specific enthalpy of the fuel–air mixture, $h_{\mathrm{f}} + \phi h_{\mathrm{a}}$, which is presumed to be the same with or without waste-heat recovery, ϕ is the molar ratio of air to fuel, and $\bar{C}_{\mathrm{p}}$ is the specific heat averaged over the exhaust-gas components. Figure 10.14, which is derived from Equation 10.20, gives possible fuel savings from using high-temperature flue gas to heat the combustion air in industrial furnaces.

It should be pointed out that the use of recovered waste heat to preheat combustion air, boiler feedwater, and product to be heat treated, confers special benefits not necessarily accruing when the heat

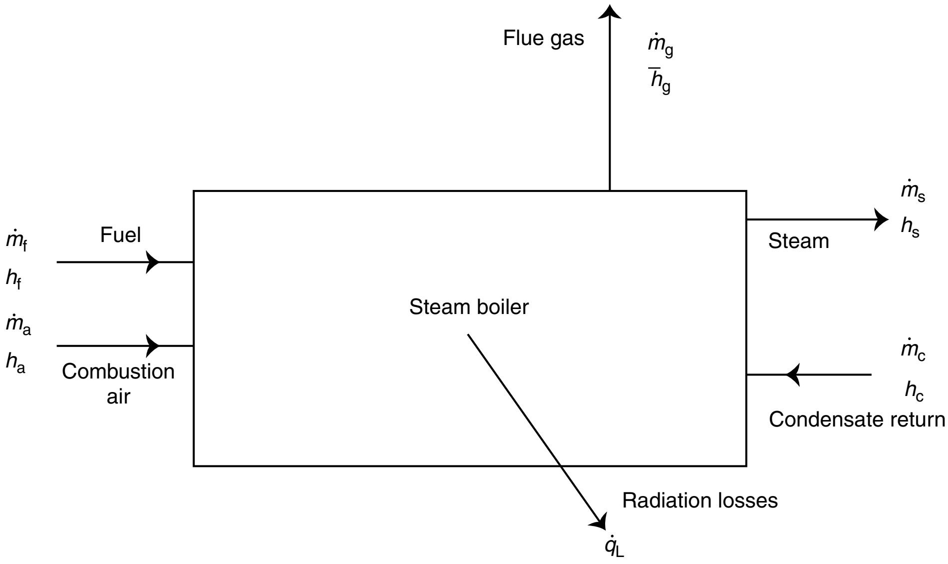

FIGURE 10.13 Heat balance on steam boiler.

is recovered to be used in another system. The preheating operation results in less fuel being consumed in the furnace, and the corresponding smaller air consumption means even smaller waste heat being ejected from the stacks.

Table 10.8 shows heat balances for a boiler with no flue gas–heat recovery, with a feedwater preheater (economizer) installed and with an air preheater, respectively.

It is seen that air preheater alone saves 6% of the fuel and the economizer saves 9.2%. Since the economizer is cheaper to install than the air preheater, the choice is easy to make for an industrial boiler. For a utility boiler, both units are invariably used in series in the exit gas stream.

Table 10.9 is an economic study using 2005 prices for fuel, labor, and equipment. At that time it was estimated that a radiation recuperator fitted to a fiberglass furnace would cost $820,200 and effect a

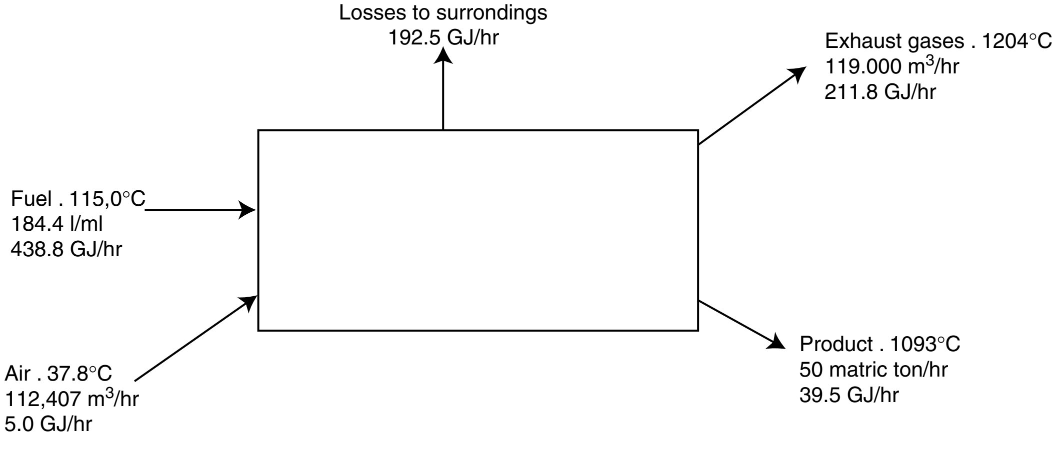

FIGURE 10.14 Heat balance for a simple continuous steel tube furnace.

TABLE 10.8 Heat Balances for a Steam Generator

Case	Input Streams				Output Streams			
	Name	Temperature (°C)	Flow Rate	Energy	Name	Temperature (°C)	Flow Rate	Energy
Without economizer or air preheater	Natural gas	26.7	3611 m^3/hr	134.78 GJ/hr	Steam	185.6	45,349 kg/hr	126.23
	Air	26.7	35,574 m^3/hr	560.32 MJ/hr	Flue gas	372.2	41,185 m^3/hr	19.49
	Makeup water	10.0	7076 kg/hr	297.25 MJ/hr	Surface losses	—	—	1.21
	Condensate return	82.2	41,277 kg/hr	14.21 GJ/hr	Blow down	185.6	2994 kg/hr	2.36
With air preheater	Natural gas	26.7	3395 m^3/hr	126.72 GJ/hr	Steam	185.6	45,359 kg/hr	126.23
	Air	232.2	32,114 m^3/hr	478.90 GJ/hr	Flue gas	260.0	35,509 m^3/hr	11.42
	Makeup water	10	70,767 kg/hr	297.25 MJ/hr	Surface losses	—	—	1.21
	Condensate return	82.2	41,277 kg/hr	14.21 GJ/hr	Blow down	185.6	2994 kg/hr	2.36
With economizer	Natural gas	26.7	3278 m^3/hr	122.37 GJ/hr	Steam	185.6	45,359 kg/hr	126.23
	Air	26.7	31,013 m^3/hr	462.48 MJ/hr	Flue gas	176.7	34,281 m^3/hr	7.08
	Makeup water	101	7076 kg/hr	297.25 GJ/hr	Surface loss	—	—	1.21
	Condensate water	82.2	41,277 kg/hr	12.21 GJ/hr	Blow down	185.6	2994 kg/hr	2.36

TABLE 10.9 Cost-Fuel Savings Analysis of a Fiberglass Furnace Recuperator

Operation	Continuous
Fuel input	19.42 GJ/hr
Fuel	No. 3 fuel oil
Furnace temperature	1482°C
Flue gas temperature entering recuperator	1204°C
Air preheat (at burner)	552°C
Fuel savings = 37.4%	
Q = 7.26 GJ/hr or 173.6 L/hr of oil	
Fuel cost savings estimation	
per GJ = $5.00	
per hour = $36.30	
per year (8,000 h) = $290,435	
Cost of recuperator	$421,400
Cost of installation, related to recuperator	$398,800
Total cost of recuperator installation	$820,200
Approximate payback time	2.82 yrs

savings of $90,435/year, making for a payoff period of approximately 2.8 years. This assumes of course that the original burners, combustion-control system, and so on, could be used without modification.

At this point, we can take some time to relate waste-heat recovery to the combustion process itself. We can first state categorically that the use of preheated combustion air improves combustion conditions and efficiency at all loads, and in a newly designed installation permits a reduction in size of the boiler or furnace. It is true that the increased mixture temperature that accompanies air preheat results in some narrowing of the mixture stability limits, but in all practical furnaces this is of small importance.

In many cases low-temperature burners may be used for preheated air, particularly if the air preheat temperature is not excessive and if the fuel is gaseous. However, the higher volume flow of preheated air in the air piping may cause large enough increases in pressure drop to require a larger combustion air fan. Of course larger diameter air piping can prevent the increased pressure drop, since air preheating results in reduced quantities of fuel and combustion air. For high preheat temperatures alloy piping, high-temperature insulation, and water-cooled burners may be required. Since many automatic combustion-control systems sense volume flows of air and/or fuel, the correct control settings will change when preheated air is used. Furthermore, if air preheat temperature varies with furnace load, then the control system must compensate for this variation with an auxiliary temperature-sensing control. On the other hand, if control is based on the oxygen content of the flue gases, the control complications arising from gas volume variation with temperature is obviated. This is the preferred control system for all furnaces, and only cost prevents its wide use in small installations. Burner operation and maintenance for gas burners is not affected by preheating, but oil burners may experience accelerated fuel coking and resulting plugging from the additional heat being introduced into the liquid fuel from the preheated air. Careful burner design, which may call for water cooling or for shielding the fuel tip from furnace radiation, will always solve the problems. Coal-fired furnaces may use preheated air up to temperatures that endanger the grates or burners. Again, any problems can be solved by special designs involving water cooling if higher air temperatures can be obtained and/or desired.

The economics of waste-heat recovery today range from poor to excellent depending upon the technical aspects of the application as detailed earlier, but the general statement can be made that, at least for most small industrial boilers and furnaces, standard designs and/or off-the-shelf heat exchangers prove to be the most economic. For large systems one can often afford to pay for special designs, construction, and installations. Furthermore, the applications are often technically constrained by material properties and space limitations, and as shall be seen later, always by economic considerations.

10.5.2.3 Heating, Ventilating, and Air-Conditioning

Heating, ventilating, and air-conditioning, while not usually important in the energy-intensive industries, may be responsible for the major share of energy consumption in the light manufacturing field, particularly in high-technology companies and those engaged primarily in assembly.

Because of air pollution from industrial processes, many HVAC systems require 100% outside ventilating air. Furthermore, ventilating air requirements are often much in excess of those in residential and commercial practice (Hayashi et al. 1985). An approximate method for calculating the total heat required for ventilating air in kJ per heating season is given by

$$\begin{aligned} E_{\mathrm{v}}(\mathrm{kJ}) &= 60 \times 24\left(\frac{\min}{\mathrm{day}}\right) \times (1.2 \times 0.519)\left(\frac{\mathrm{kJ}}{\mathrm{m}^3 - \mathrm{K}^{\circ}}\right) \times \mathrm{SCMM} \times \mathrm{DD} \\ &= 896.8 \times \mathrm{SCMM} \times \mathrm{DD} \qquad (10.21) \end{aligned}$$

where SCMM = standard cubic meter per minute of total air entering plant including unwanted infiltration; DD = heating degree-days (C).

This underestimates the energy requirement, because degree-days are based on 18.33°C reference temperature and indoor temperatures are ordinarily held 1.6–3.9° higher. For a location with 3333 degree-days each year the heating energy given by Equation 10.13 is about 17% low.

Savings can be effected by reducing the ventilating air rate to the actual rate necessary for health and safety and by ducting outside air into direct-fired heating equipment such as furnaces, boilers, ovens, and dryers. Air infiltration should be prevented through a program of building maintenance to replace broken windows, doors, roofs, and siding, and by campaigns to prevent unnecessary opening of windows and doors.

Additional roof insulation is often economic, particularly because thermal stratification makes roof temperatures much higher than average wall temperatures. Properly installed vertical air circulators can prevent the vertical stratification and save heat loss through the roof. Windows can be double glazed, storm windows can be installed, or windows can be covered with insulation. Although the benefits of natural lighting are eliminated by this measure, it can be very effective in reducing infiltration and heat transfer losses.

Waste heat from ventilating air itself, from boiler and furnace exhaust stacks, and from air-conditioning refrigeration compressors can be recovered and used to preheat makeup air. Consideration should also be given to providing spot ventilation in hazardous locations instead of increasing general ventilation air requirements.

As an example of the savings possible in ventilation air control, a plant requiring 424.5 CMM outside airflow is selected. A gas-fired boiler with an energy input of 0.0165 GJ is used for heating and is supplied with room air.

$$\text{Combustion air} = \frac{16.5 \times 10^6}{37{,}281} \times \frac{12}{60} = 88.52\ \text{CMM}$$

for a fuel with 37,281 kJ/m^3 heating value and an air fuel ratio of 12 m^3 air per m^3 fuel. The number of annual degree-days was 3175.

A study showed that the actual air supplied through infiltration and air handlers was 809 m^3/min. An outside air duct was installed to supply combustion air for the boiler and the actual ventilating air supply was reduced to the required 424 m^3/min. The fuel saving that resulted using Equation 10.21 was

$$896.8(809 - 424)\ 3{,}175 = 1{,}096.2\ \text{GJ}$$

worth $5482 in fuel at $5.00/GJ for natural gas.

10.5.2.4 Modifications of Unit Processes

The particular process used for the production of any item affects not only the cost of production but also the quality of the product. Since the quality of the product is critical in customer acceptance and therefore in sales, the unit process itself cannot be considered a prime target for the energy conservation program. That does not say that one should ignore the serendipitous discovery of a better and cheaper way of producing something. Indeed, one should take instant advantage of such a situation, but that clearly is the kind of decision that management could make without considering energy conservation at all.

10.5.2.5 Optimizing Process Scheduling

Industrial thermal processing equipment tends to be quite massive compared to the product treated. Therefore, the heat required to bring the equipment to steady-state production conditions may be large enough to make start-ups fuel intensive. This calls for scheduling this equipment so that it is in use for as long periods as can be practically scheduled. It also may call for idling the equipment (feeding fuel to keep the temperature close to production temperature) when it is temporarily out of use. The fuel rate for idling may be between 10 and 40% of the full production rate for direct-fired equipment. Furthermore, the stack losses tend to increase as a percentage of fuel energy released. It is clear that overfrequent start-ups and long idling times are wasteful of energy and add to production costs. The hazards of eliminating some of that waste through rescheduling must not be taken lightly. For instance, a holdup in an intermediate heating process can slow up all subsequent operations and make for inefficiency down the line. The breakdown of a unit that has a very large production backlog is much more serious than that of one having a smaller backlog. Scheduling processes in a complex product line is a very difficult exercise and perhaps better suited to a computerized PERT program than to an energy conversation engineer. That does not mean that the possibilities for saving through better process scheduling should be ignored. It is only a warning to move slowly and take pains to find the difficulties that can arise thereby.

A manufacturer of precision instruments changed the specifications for the finishes of over half of his products, thereby eliminating the baking required for the enamel that had been used. He also rescheduled the baking process for the remaining products so that the oven was lighted only twice a week instead of every production day. A study is now proceeding to determine if electric infrared baking will not be more economic than using the gas-fired oven.

10.5.2.6 Cogeneration of Process Steam and Electricity

In-plant (or on-site) electrical energy cogeneration is nothing new. It has been used in industries with large process steam loads for many years, both in the U.S. and Europe. It consists of producing steam at a higher pressure than required for process use, expanding the high-pressure steam through a back-pressure turbine to generate electrical energy, and then using the exhaust steam as process steam. Alternatively, the power system may be a diesel engine that drives an electrical generator. The diesel engine exhaust is then stripped of its heat content as it flows through a waste-heat boiler where steam is generated for plant processes. A third possibility is operation of a gas-turbine generator to supply electric power and hot exhaust gases, which produce process steam in a waste-heat boiler. As will be seen later, the ratio of electric power to steam-heat rate varies markedly from one of these types of systems to the next. In medium to large industrial plants the cogeneration of electric power and process steam is economically feasible provided certain plant energy characteristics are present. In small plants or in larger plants with small process steam loads, cogeneration is not economic because of the large capital expenditure involved. Under few circumstances is the in-plant generation of electric power economic without a large process steam requirement. A small industrial electric plant cannot compete with an electric utility unless the generation required in-plant exceeds the capacity of the utility. In remote areas where no electric utility exists, or where its reliability is inferior to that of the on-site plant, the exception can be made.

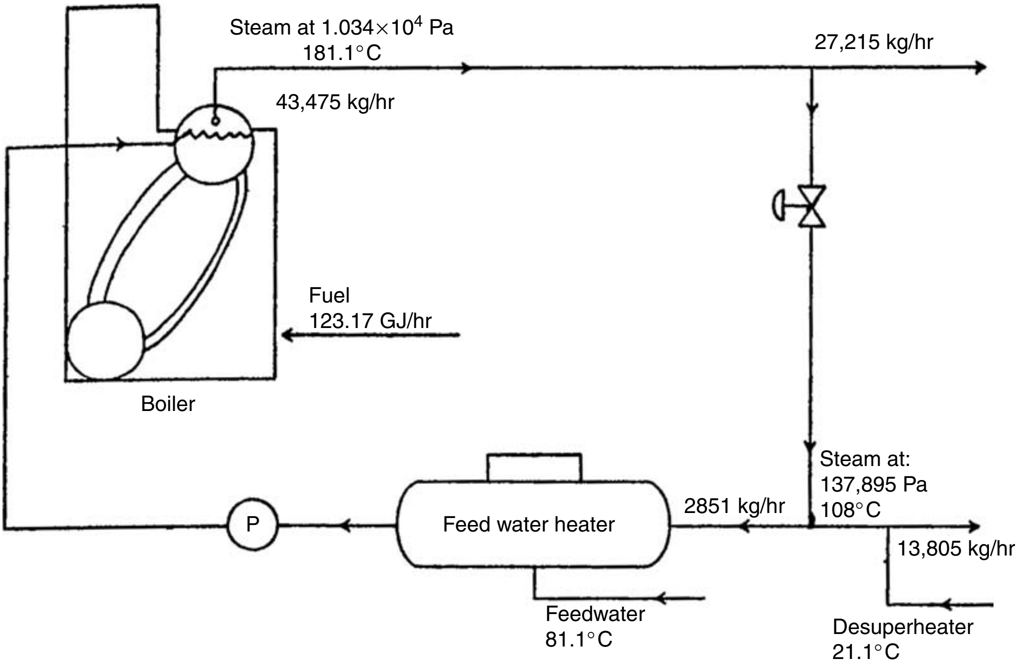

FIGURE 10.15 Steam plant schematic before adding electrical generation.

Cogeneration if applied correctly is not only cost-effective, it is fuel conserving. That is, the fuel for the on-site plant is less than that used jointly by the utility to supply the plant's electric energy and that used on-site to supply process steam. Figure 10.15 and Figure 10.16 illustrate the reasons for and the magnitude of the savings possible. However, several conditions must be met in order that an effective application be possible. First, the ratio of process steam heat rate to electric power must fall close to these given in the table below:

Heat Engine Type	$E_{\text{stream}}/E_{\text{elect}}$
Steam turbine	2.3
Gas turbine	4.0
Diesel engine	1.5

The table is based upon overall electric plant efficiencies to 30, 20, and 40% respectively, for steam turbine, gas turbine, and diesel engine. Second, it is required that the availability of the steam load coincide closely with the availability of the electric load. If these temporal availabilities are out of phase, heat-storage systems will be necessary and the economy of the system altered. Third, it is necessary to have local electric utility support. Unless backup service is available from your utility, the cost of building in redundancy is too great. This may be the crucial factor in some cases. The subject of cogeneration and the available technology is covered in Chapter 4.

10.5.2.7 Commercial Options in Waste-Heat Recovery Equipment

The equipment that is useful in recovering waste heat can be categorized as heat exchangers, heat-storage systems, combination heat storage-heat exchanger systems, and heat pumps.

Heat exchangers certainly constitute the largest sales volume in this group. They consist of two enclosed flow paths and a separating surface that prevents mixing, upports any pressure difference

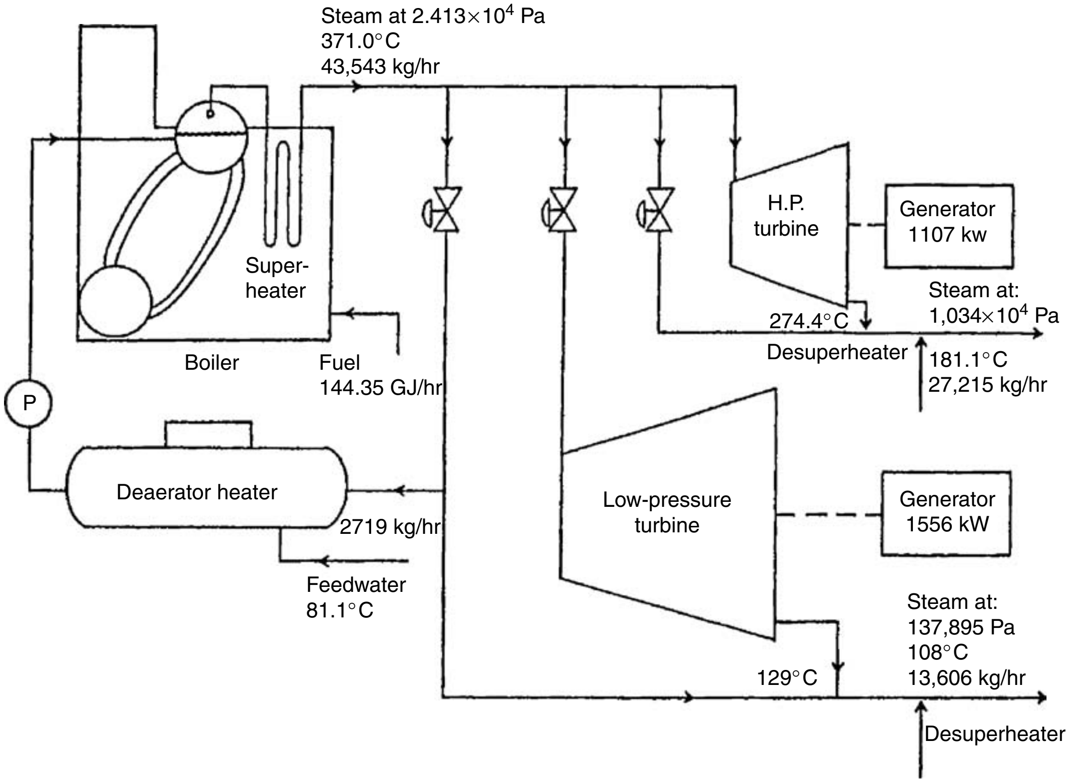

FIGURE 10.16 Steam plant schematic after installing electrical generation.

between the fluids of the two fluids, and provides the means through which heat is transferred from the hotter to the cooler fluid. These are ordinarily operated at steady-state-steady-flow condition. The fluids may be gases, liquids, condensing vapors, or evaporating liquids, and occasionally fluidized solids.

Radiation recuperators are high-temperature combustion-air preheaters used for transferring heat from furnace exhaust gases to combustion air. As seen in Figure 10.17 they consist of two concentric cylinders, the inner one as a stack for the furnace and the concentric space between the inner and outer cylinders as the path for the combustion air, which ordinarily moves upward and therefore parallel to the flow of the exhaust gases. With special construction materials these can handle 1355°C furnace gases and save as much as 30% of the fuel otherwise required. The main problem in their use is damage due to overheating for reduced airflow or temperature excursions in the exhaust-gas flow.

Convective air preheaters are corrugated metal or tubular devices that are used to preheat combustion air in the moderate temperature range (121°C–649°C) for ovens, furnaces, boilers, and gas turbines, or to preheat ventilating air from sources as low in temperature as 21°C. Figure 10.18 and Figure 10.19 illustrate typical construction. These are often available in modular design so that almost any capacity and any degree of effectiveness can be obtained by multiple arrangements. The biggest problem is keeping them clean.

Economizer is the name traditionally used to describe the gas-to-liquid heat exchanger used to preheat the feedwater in boilers from waste heat in the exhaust-gas stream. These often take the form of loops, spiral or parallel arrays of finned tubing through which the feedwater flows and over which the exhaust gases pass. They are available in modular form to be introduced into the exhaust stack or into

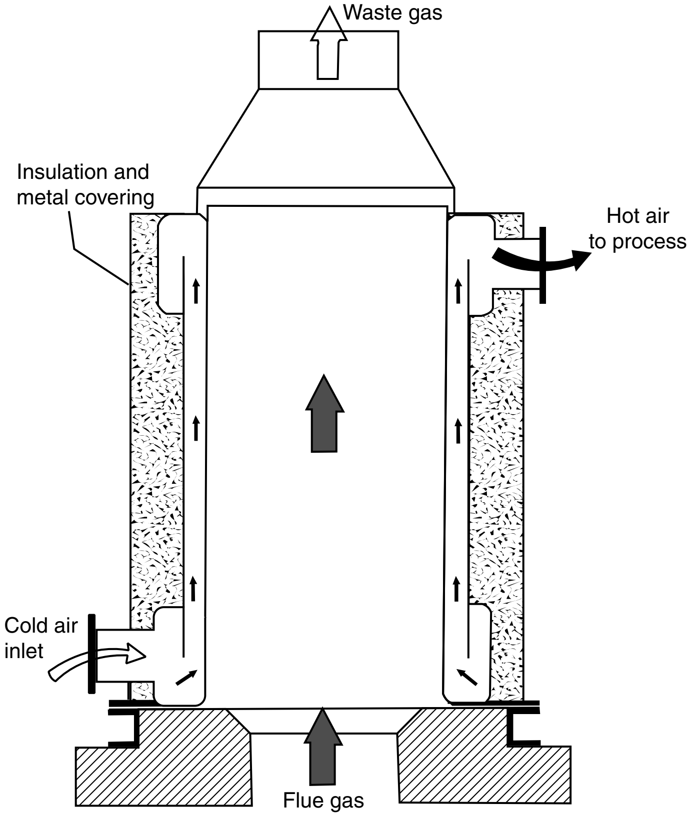

FIGURE 10.17 Metallic radiation recuperator.

the breeching. They can also be used in reverse to heat air or other gases with waste heat from liquid streams.

A more recent development is the use of condensing economizers which are placed in the exhaust stream following high-temperature economizers. They are capable of extracting an additional 6%–8% of the fuel input energy from the boiler exhaust gases. However, they are only used under certain restricted conditions. Obviously, the cooling fluid must be at a temperature below the dew point of the exhaust stream. This condition is often satisfied when boilers are operated with 100% make-up water. A second, less restrictive condition is that the flue gases be free of sulfur oxides. This is normally the case for natural gas-fired boilers. Otherwise the economizer tubes will be attacked by sulfurous and/or sulfuric acid. Acid corrosion can be slowed down markedly by the use of all-stainless steel construction, but the cost of the equipment is increased significantly.

Heat-pipe arrays are often used for air-to-air heat exchangers because of their compact size. Heat-transfer rates per unit area are quite high. A disadvantage is that a given heat pipe (that is, a given internal working substance) has a limited temperature range for efficient operation. The heat pipe transfers heat from the hot end by evaporative heating and at the cold end by condensing the vapor. Figure 10.20 is a sketch of an air preheater using an array of heat pipes.

Waste-heat boilers are water-tube boilers, usually prefabricated in all but the largest sizes, used to produce saturated steam from high-temperature waste heat in gas streams. The boiler tubes are often finned to keep the dimensions of the boiler smaller. They are often used to strip waste heat from diesel-engine exhausts, gas-turbine exhausts, and pollution-control incinerators or afterburners. Figure 10.21 is

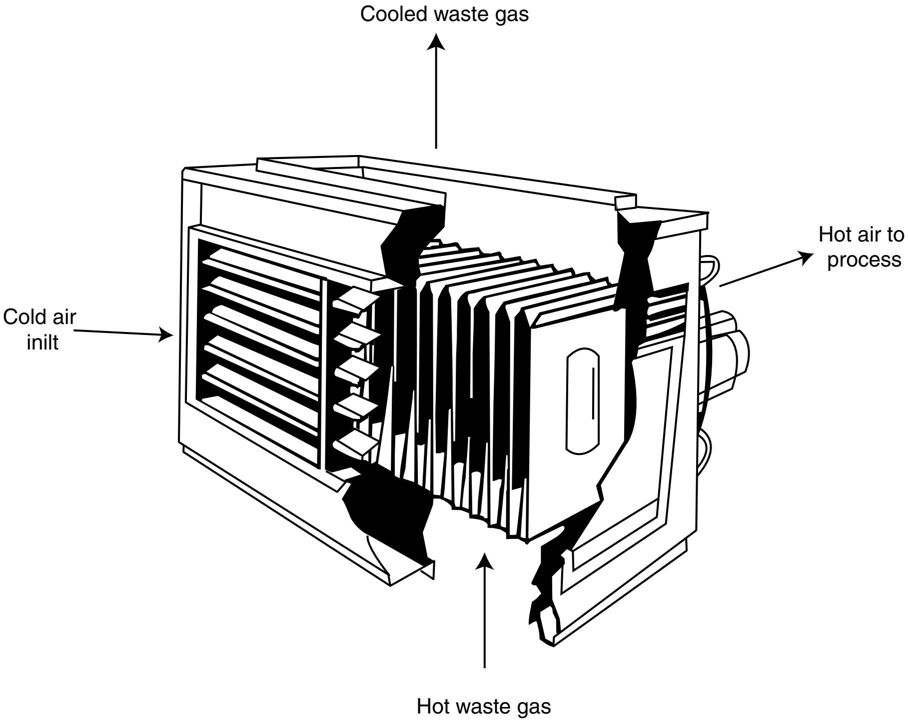

FIGURE 10.18 Air preheater.

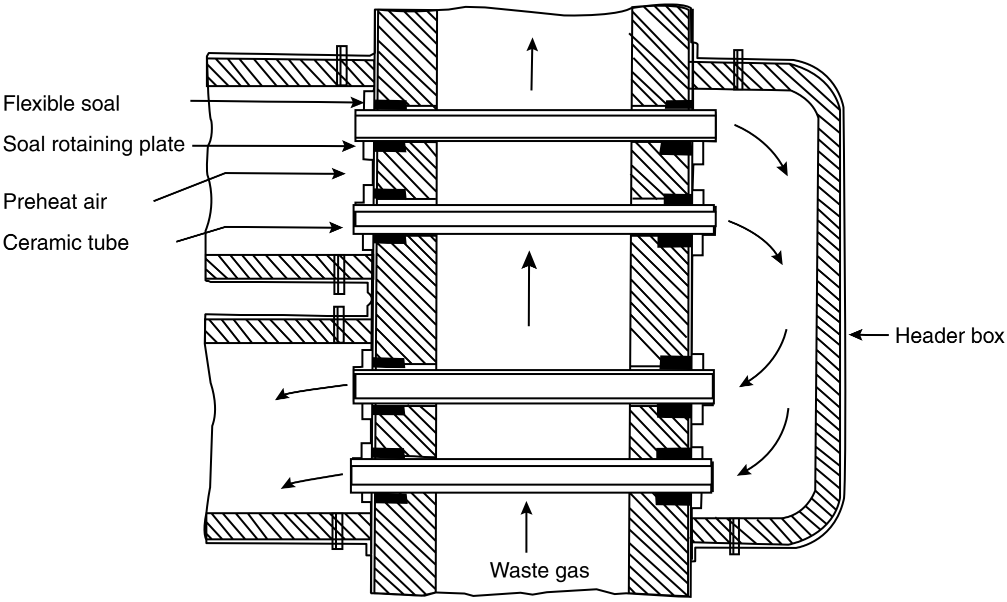

FIGURE 10.19 Ceramic tube recuperator.

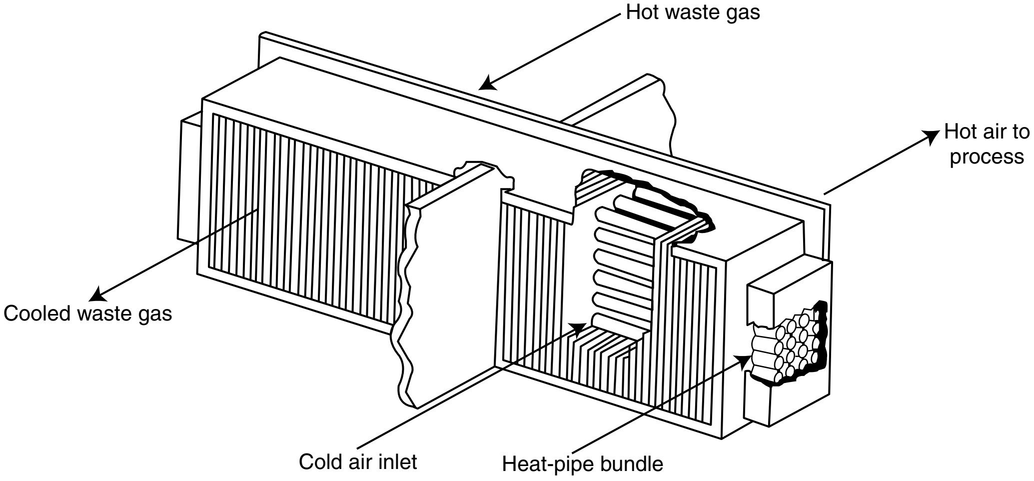

FIGURE 10.20 Heat-pipe recuperator.

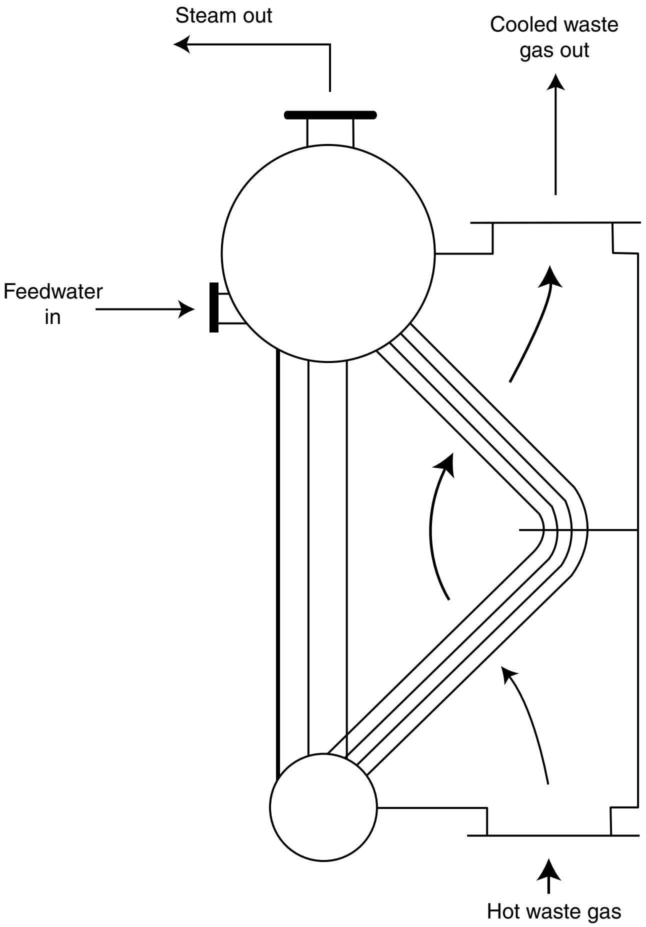

FIGURE 10.21 Waste-heat boiler.

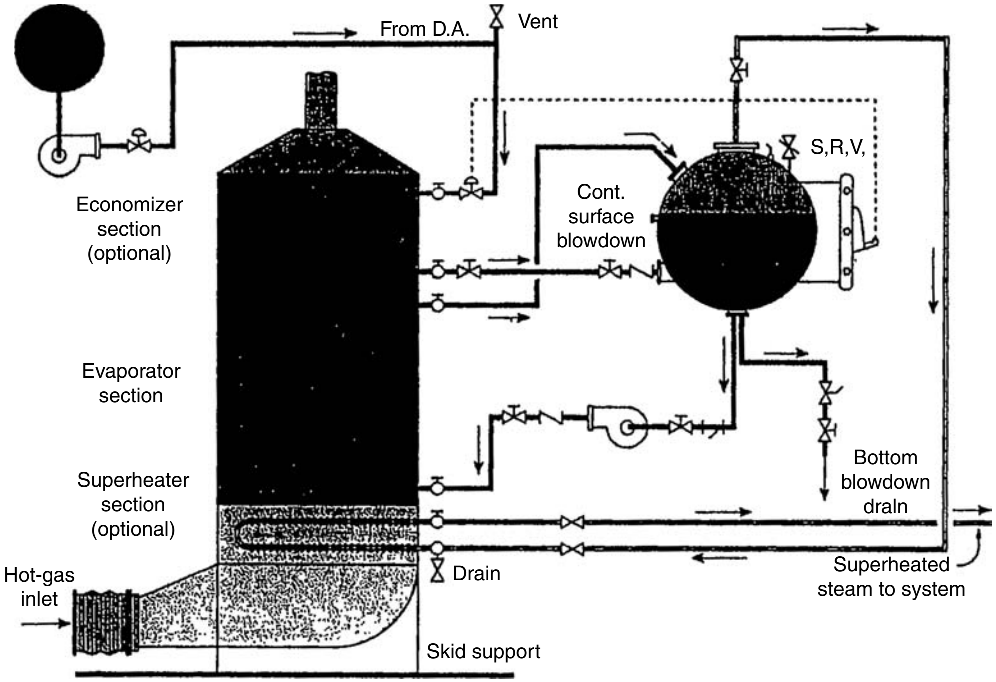

FIGURE 10.22 Schematic diagram of a finned-tube waste-heat boiler. (Courtesy Cannon Technology.)

a diagram of the internals of a typical waste-heat boiler. Figure 10.22 is a schematic diagram showing a waste-heat boiler for which the evaporator is in the form of a finned-tube economizer. Forced water circulation is used giving some flexibility in placing the steam drum and allowing the use of smaller tubes. It also allows the orientation of the evaporator to be either vertical or horizontal. Other advantages of this design are the attainment of high boiler efficiencies, a more compact boiler, less cost to repair or retube, the ability to make superheated steam using the first one or more rows of downstream tubes as the superheater, and the elimination of thermal shock, since the evaporator is not directly connected to the steam drum.

Heat-storage systems, or regenerators, once very popular for high-temperature applications, have been largely replaced by radiation recuperators because of the relative simplicity of the latter. Regenerators consist of twin flues filled with open ceramic checkerwork. The high-temperature exhaust of a furnace flowing through one leg of a swing valve to one of the flues heated the checkerwork while the combustion air for the furnace flowed through the second flue in order to preheat it. When the temperatures of the two masses of checkerwork were at proper levels, the swing valve was thrown and the procedure was continued, but with reversed flow in both flues. Regenerators are still used in some glass- and metal-melt furnaces, where they are able to operate in the temperature range 1093°C–1649°C. It should be noted that the original application of the regenerators was to achieve the high-melt temperatures required with low-heating-value fuel.

A number of ceramic materials in a range of sizes and geometric forms are available for incorporation into heat-storage units. These can be used to store waste heat in order to remedy time discrepancies between source and load. A good example is the storage of solar energy in a rock pile so that it becomes available for use at night and on cloudy days. Heat storage, other than for regenerators in high-temperature applications, has not yet been used a great deal for waste-heat recovery but will probably become more popular as more experience with it accumulates.

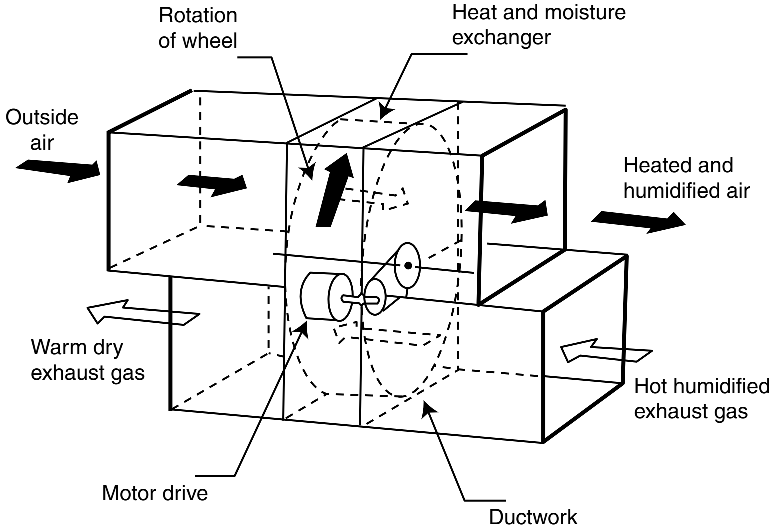

FIGURE 10.23 Heat Wheel.

Combination heat-storage unit-heat exchangers called heat wheels are available for waste-heat recovery in the temperature range 0°C–982°C. The heat wheel is a porous flat cylinder that rotates within a pair of parallel ducts, as can be observed in Figure 10.23. As the hot gases flow through the matrix of the wheel they heat one side of it, which then gives up that heat to the cold gases as it passes through the second duct. Heat-recovery efficiencies range to 80%. In low- and moderate-wire matrix of the same material. In the high-temperature range the material is ceramic. In order to prevent cross-contamination of the fluid streams, a purge section, cleared by fresh air, can be provided. If the matrix of the wheel is covered with a hygroscopic material, latent heat as well as sensible heat can be recovered. Problems encountered with heat wheels include freeze damage in winter, seal wear, and bearing maintenance in high-temperature applications.

The heat pump is a device operating on a refrigeration cycle that is used to transfer energy from a low-temperature source to a higher temperature load. It has been highly developed as a domestic heating plant using energy from the air or from well but has not been used a great deal for industrial applications. The COP (or the ratio of heat delivered to work input) for an ideal Carnot refrigeration cycle equals $T_H/(T_H - T_L)$, where T_H is the load temperature and T_L is the source temperature. It is obvious that when the temperature difference $T_H - T_L$ becomes of the order of T_H, the heat could be derived almost as cheaply from electric resistance heating. However for efficient refrigeration machines and a small temperature potential to overcome, the actual COP is favorable to moderate-cost waste energy. The heat pump can be used to transfer waste heat from and to any combination of liquid, gas, and vapor.

10.6 The Role of New Equipment and Technology in Industrial Energy Efficiency

10.6.1 Industrial Energy Savings Potential

The last part of Section 10.4 pointed to several studies of industrial energy efficiency that showed that a 20% reduction could be accomplished in a relatively easy and cost-effective manner. The purpose of this section is to provide the equipment, technology, and operational changes that could lead to industrial energy savings on the order of 20% or more.

10.6.2 The U.S. DOE Energy-Loss Study and the NAM Efficiency and Innovation Study

The most recent major study on the potential for improving energy efficiency in industry was conducted for the U.S. Department of Energy, Office of Industrial Technologies, for their ITP in December 2004. This study was called the "Energy Use, Loss and Opportunities Analysis: U.S. Manufacturing and Mining."[1] This study was then used by the NAM together with the Alliance to Save Energy to produce a report on the "Efficiency and Innovation in U.S. Manufacturing Energy Use"[4] Both the U.S. DOE/OIT and NAM conclude that there is a significant opportunity for reducing industrial energy use by 20%.

As stated in the NAM report, "[i]ndustry's best R&D options for reducing energy costs were summarized in a study sponsored by the U.S. DOE. This study identifies energy-efficiency opportunities that yield energy, economic and environmental benefits, primarily for large volume, commodity/process industries. Opportunities were prioritized to reflect the magnitude of potential savings, broadness of suitability across industries, and feasibility to implement. In total, these energy-saving opportunities represent 5.2 quadrillion BTU—21% of primary energy consumed by the manufacturing sector. These savings equate to almost $19 billion for manufacturers, based on 2004 energy prices and consumption volumes." Table 10.10 summarizes these leading opportunities. An expanded version of this information appears in Table 10.11.

10.6.3 The ACEEE Fan and Pump Study

In April 2003, the ACEEE released a report on their study "Realizing Energy Efficiency Opportunities in Industrial Fan and Pump Systems." They concluded that fans and pumps account for more than a quarter of industrial electricity consumption, and that optimization of the operation of these fans and

TABLE 10.10 Industries' Best Opportunities for Future Energy Savings

Top R&D Opportunities for Energy Savings in Commodity/Process Manufacturing; Initiatives that Provide the Largest Energy and Dollar Savings

Type of Opportunity[a]	Total Energy Savings		Total Cost Savings	
	(trillion BTU)	Percent of Total %	($mill.)	Percent of Total %
Waste heat and energy recovery	1831	35	$6408	34
Improvements to boilers, fired systems, process heaters, and cooling opportunities	907	17	$3077	16
Energy system integration and best practices opportunities	1438	28	$5655	30
Energy source flexibility and combined heat and power	828	16	$3100	16
Improved sensors, controls, automation and robotics for energy systems	191	4	$630	3
Totals	5195		$18,870	

[a] See Appendix A for an expanded version of this table.

Source: From U.S. Department of Energy, Industrial Technologies Program. See References section (DOE-TP, 2004); *NAM, Efficiency and Innovation in U.S. Manufacturing Energy Use*, National Association of Manufacturers, Washington, DC, 2005.

TABLE 10.11 Top R&D Opportunities for Industrial Energy Savings

Top R&D Opportunities for Energy Initiatives that Provide the Largest Energy	Savings in Commodity/Process Manufacturing and Dollar Savings	Total Energy Savings		Total Cost Savings	
Type of Opportunity	Leading Industry Recipients	(trillion Btu)	Percent of Total %	($mil.)	Percent of Total %^{a}
Waste Heat and Energy Recovery		1831	35	$6408	34
…from gases and liquids, including hot gas cleanup and dehydration of liquid waste streams	Chemicals, petroleum, forest products	851	16	$2271	12
…from drying processes	Chemicals, forest products, food processing	377	7	$1240	7
…from gases in metals and nonmetallic minerals manufacture (excluding calcining), including hot gas cleanup	Iron and steel, cement	235	5	$1133	6
…from by-product gases	Petroleum, iron and steel	132	3	$750	4
…using energy export and co-location (fuels from pulp mills, forest bio-refineries, co-location of energy sources/sinks)	Forest products	105	2	$580	3
…from calcining (not flue gases)	Cement, forest products	74	1	$159	1
…from metal quenching/cooling processes	Iron and steel, cement	57	1	$275	1
Improvements to Boilers, Fired Systems, Process Heaters and Cooling Opportunities		907	17	$3077	16
Advanced industrial boilers	Chemicals, forest products, petroleum, steel, food processing	400	8	$1090	6
Improved heating/heat transfer systems (heat exchangers, new materials, improved heat transport)	Petroleum, chemicals	260	5	$860	5
Improved heating/heat transfer for metals, melting, heating, annealing (cascade heating, batch to continuous process, improved heat channeling, modular systems)	Iron and steel, metal casting, aluminum	190	4	$915	5
Advanced process cooling and refrigeration	Food processing, chemicals, petroleum and forest products	57^b	1	$212	1
Energy System Integration and Best Practices Opportunities		1438	28	$5655	30
* Steam best practices (improved generation, distribution and recovery), not including advanced boilers	All manufacturing	310	6	$850	5
* Pump system optimization	All manufacturing	302^b	6	$1370	7
* Energy system integration	Chemicals, petroleum, forest products, iron and steel, food, aluminum	260	5	$860	5
* Energy-efficient motors and rewind practices	All manufacturing	258^b	5	$1175	6
* Compressed-air system optimization	All manufacturing	163^b	3	$740	4
* Optimized materials processing	All manufacturing	145^b	3	$660	3
Energy Source Flexibility and Combined Heat and Power		828	16	$3100	16
* Combined heat and power onsite in manufacturers' central plants, producing both thermal and electricity needs	Forest products, chemicals, food processing, metals, machinery	634	12	$2000	11

Energy source flexibility (heat-activated power generation, waste steam for mechanical drives, indirect vs. direct heat vs. steam)	Chemicals, petroleum, forest products, iron and steel	194	4	$1100	6
Improved Sensors, Controls, Automation and Robotics for Energy Systems	Chemicals, petroleum, forest products, iron and steel, food, cement, aluminum	191	4	$630	3
Totals		5195		$18,870	

Note: All are R&D opportunities except for items denoted by an asterisk (*), which are near-term best practices, applicable to current assets.

[a] Totals may not add up due to rounding.

[b] Energy savings figures include the corresponding recapture of losses inherent in electricity generation, transmission, and distribution.

Source: From U.S. DOE, Office of Industrial Technologies, Industrial Technology Program, *Annual Report: Technology, Delivery, Industry of the Future*, U.S. Department of Energy, Washington, DC, 2004.

pumps could achieve electricity savings ranging from 20% to well over 50% of this category of use.[11] This report says that most optimization projects involve greater engineering costs than equipment costs, but the average payback for a good optimization project is about 1.2 years, with the cost of saved energy on the order of $0.012/kWh. In addition, these estimates do not account for productivity gains known to exist at many of the plant sites, which are sometimes as much as two to five times the energy savings.

This ACEEE report contains some excellent data on motor systems end use that is very difficult to find in general. Their data shows that 40% of industrial motor use is for fans and pumps. Because the MECS data from EIA shows that about 68% of electric use in industry is motors, this leads to the fraction of industrial electric use from fans and pumps to be (0.68)*(0.4) = 0.32, or 32%. The end use data from ACEEE is reproduced below in Table 10.12.

To see the final impact of this estimate of industrial energy savings, now apply the ACEEE estimates of 20% to 50% savings on fan and pump energy to the 32% fraction of fan and pump contribution to the total industrial electricity use. Thus, the overall savings are in the range (0.2)*(0.32) = 6.4% to (0.5)*(0.32) = 16%. Just this opportunity alone could result in achieving over half of the 20% savings contained in the U.S. DOE/OIT study.

Table 10.13 presents the ACEEE estimates of the relative magnitude of electricity consumed by fans and pump systems for the important industries on a national basis.

10.6.4 The LBL/ACEEE Study of Emerging Energy-Efficient Industrial Technologies

In October 2000, ACEEE released a report of a study they did in conjunction with staff from Lawrence Berkeley Laboratories (LBL), where they identified 175 emerging energy-efficient technologies, and honed this list down to 32 technologies that had a high likelihood of success and a high energy savings.[27] An interesting aspect of this study is that it shows that the U.S. is not running out of technologies to improve energy efficiency and economic and environmental performance, and will not run out in the future. The study shows that many of the technologies have important nonenergy benefits, ranging from reduced environmental impact to improved productivity. Several technologies have reduced capital costs compared to the current technology used by those industries. Nonenergy benefits such as these are frequently a motivating factor in bringing this kind of technology to market.

The LBL/ACEEE list of 32 most beneficial technologies is shown in Table 10.14.

TABLE 10.12 National Industrial Motor Systems Energy End Use

Pumps	25%
Materials processing	22%
Compressed air	16%
Fans	14%
Material handling	12%
Refrigeration	7%
Other	4%

Source: From Elliott, R. N., and Nadel, S., *Realizing Energy Efficiency Opportunities in Industrial Fan and Pump Systems*, Report A034, American Council for an Energy Efficient Economy, Washington, DC, 2003.

TABLE 10.13 Characterization of Industrial Fan and Pump Load in the United States

NAICS	Industry	Electricity Demand 1997	Pumps (%)	Fans and Blowers (%)	Total Motors (%)	Motor Electricity	Fans/Pumps Share of Electricity (%)	Fans/Pumps Electricity Use
11	Agriculture	16,325	25	20	75	12,244	45	7346
22	Mining	85,394	7	21	90	76,854	29	24,363
311	Food mfg.	66,166	11	5	81	53,756	16	10,809
314	Textile product mills	5135	14	15	82	4221	30	1523
321	Wood product mfg.	21,884	4	10	80	17,464	14	3064
322	Paper mfg.	119,627	28	16	84	101,078	44	52,636
324	Petroleum and coal products mfg.	69,601	51	13	85	59,369	63	44,061
325	Chemical mfg.	212,709	18	8	73	154,693	26	54,797
326	Plastics & rubber mfg.	52,556	9	4	66	34,847	13	6729
327	Nonmetallic minerals product mfg.	37,416	4	4	65	24,328	8	3037
331	Primary metal mfg.	172,518	2	4	26	44,855	6	10,351
332	Fabricated metal product mfg.	49,590	7	5	65	32,462	12	6149
333	Machinery mfg.	27,295	8	4	67	18,391	12	3330
334	Computer & electronic product mfg.	40,099	2	3	54	21,783	4	1801
336	Transportation equipment mfg.	54,282	4	6	64	34,629	11	5753
	Total	1,030,598				690,974		235,750
				Fraction of total elec.		67%		23%

TABLE 10.14 Technologies with High Energy Savings and a High Likelihood of Success

Technology	Code	Total Energy Savings	Likelihood of Success	Recommended Next Steps
Efficient cell retrofit designs	Alum-2	High	High	Demo
Advanced lighting technologies	Lighting-1	High	High	Dissem., demo
Advance ASD designs	Motorsys-1	High	High	R&D
Membrane technology wastewater	Other-3	High	High	Dissem., R&D
Sensors and controls	Other-5	High	High	R&D, demo, dissem.
Black liquor gasification	Paper-1	High	High	Demo
Near net shape casting/strip casting	Steel-2	High	High	R&D
New EAF furnace processes	Steel-3	High	High	Field test
Oxy-fuel combustion in reheat furnace	Steel-4	High	High	Field test
Advanced CHP turbine systems	Utilities-1	High	High	Policies
Autothermal reforming-ammonia	Chem-7	High	Medium	Dissemination
Membrane technology—food	Food-3	High	Medium	Dissem., R&D
Advanced lighting design	Lighting-2	High	Medium	Dissem., demo
Compressed-air system management	Motorsys-3	High	Medium	Dissem.
Motor system optimization	Motorsys-5	High	Medium	Dissem., training
Pump efficiency improvement	Motorsys-6	High	Medium	Dissem., training
High-efficiency/low NOX burners	Other-2	High	Medium	Dissem., demo
Process integration (pinch analysis)	Other-4	High	Medium	Dissemination
Heat recovery—paper	Paper-5	High	Medium	Demo
Impulse drying	Paper-7	High	Medium	Demo
Smelting reduction processes	Steel-5	High	Medium	Demo
Advanced reciprocating engines	Utilities-2	High	Medium	R&D, demo
Fuel cells	Utilities-3	High	Medium	Demo
Microturbines	Utilities-4	High	Medium	R&D, demo
Inert anodes/wetted cathodes	Alum-4	High	Medium	R&D
Advanced forming	Alum-1	Medium	High	R&D
Plastics recovery	Chem-8	Medium	High	Demo
Continuous melt silicon crystal growth	Electron-1	Medium	High	R&D
100% recycled glass cullet	Glass-1	Medium	High	Demo
Anaerobic wastewater treatment	Other-1	Medium	High	Dissem., demo
Dry sheet forming	Paper-4	Medium	High	R&D, demo
Biodesulfurization	Refin-1	Medium	High	R&D, demo

Technologies in this table are listed in alphabetical order based on industry sector.

10.7 Conclusion

Energy is the lifeblood of industry; it is used to convert fuels to thermal, electric, or motive energy to manufacture all the products of daily life. Using this energy efficiently is a necessity to keep industries competitive, clean, and at their peak of productivity. Energy management programs that improve the operational efficiency and the technological efficiency of industry are critical to the long-term success of industry and manufacturing in the U.S. One important result in this area has been a recognition that the U.S. is not running out of technologies to improve industrial energy efficiency, productivity, and environmental performance, and it is not going to run out in the foreseeable future. A substantial opportunity to the country's industrial energy use by over 20% is currently available using better operational procedures and using improved equipment in industrial plants. These savings to industry are worth almost $19 billion at 2004 energy prices. With crude oil prices edging toward $70 in late summer 2005, this dollar savings amount should be substantially higher. It is time to capture the benefits of this opportunity.

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11

Electric Motor Systems Efficiency

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11.1 Introduction

Motor systems are by far the most important type of electrical load, ranging from small fractional hp motors incorporated in home appliances to multi-megawatt motors driving pumps and fans in power plants. Motors consume over half of the total electricity, and in industry they are responsible for about two-thirds of the electricity consumption. In the commercial and residential sectors motors consume slightly less than half of the electricity. The cost of powering motors is immense; roughly $100 billion a year in the U.S. alone. There is a vast potential for saving energy and money by increasing the efficiency of motors and motor systems.

11.1.1 Motor Types

Motors produce useful work by causing the shaft to rotate. Motors have a rotating part, the rotor, and a stationary part, the stator. Both parts produce magnetic fields, either through windings excited by electric currents or through the use of permanent magnets. It is the interaction between these two magnetic fields which is responsible for the torque generation, as shown in Figure 11.1.

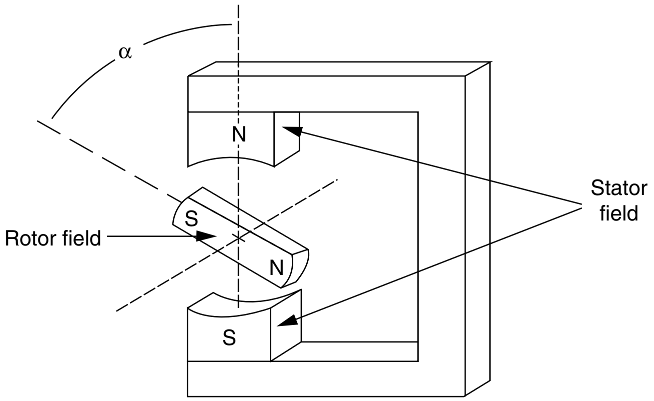

FIGURE 11.1 Torque generation in a motor. The generated torque is proportional to the strength of each magnetic field and depends on the angle α between the two fields. Mathematically, torque equals $|\mathbf{B}_{\text{rotor}}| \times |\mathbf{B}_{\text{stator}}| \times \sin \alpha$, where **B** refers to a magnetic field. (Reprinted from *Energy-Efficient Motor Systems: A Handbook on Technology, Program and Policy Opportunities*, 1992, American Council for an Energy Efficient Economy, Washington, D.C. With permission.)

There are a wide variety of electric motors, based on the type of power supply (AC or DC) that feeds the windings, as well as on different methods and technologies to generate the magnetic fields in the rotor and in the stator. Figure 11.2 presents the most important types of motors.

Because of their low cost, high reliability and fairly high efficiency, most of the motors used in large home appliances, industry, and commercial buildings are induction motors. Figure 11.3 shows the operating principle of a three-phase induction motor.

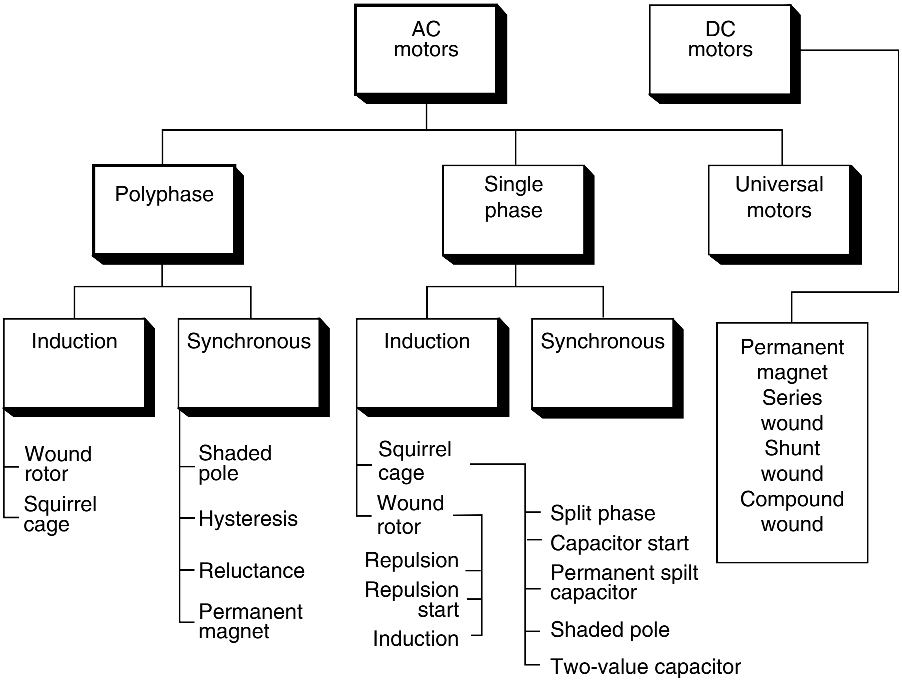

FIGURE 11.2 Motor types. (From EPRI, 1992a.)

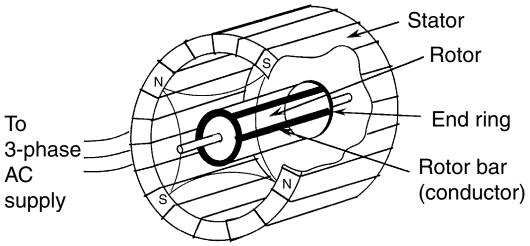

FIGURE 11.3 Operation of a four-pole squirrel-cage induction motor. Rotating magnetic field is created in the stator by AC currents carried in the stator winding. Three-phase voltage source results in the creation of north and south magnetic poles that revolve or "move around" the stator. The changing magnetic field from the stator induces current in the rotor conductors, in turn creating the rotor magnetic field. Magnetic forces in the rotor tend to follow the stator magnetic fields, producing rotary motor action.

Synchronous motors are used in applications requiring constant speed, high operating efficiency and controllable power factor. Efficiency and power factor are particularly important above 1000 hp. Although DC motors are easy to control, both in terms of speed and torque, they are expensive to produce and have modest reliability. DC motors are used for some industrial and electric traction applications, but their importance is dwindling.

11.2 Motor Systems Efficiency

The efficiency of a motor-driven process depends upon several factors which may include:

- Motor efficiency
- Motor speed controls
- Proper sizing
- Power supply quality
- Distribution losses
- Transmission
- Maintenance
- Driven equipment (pump, fan, etc.) mechanical efficiency.

It must be emphasized that the design of the process itself influences the overall efficiency (units produced/kWh or service produced/kWh) to a large extent. In fact, in many systems the largest opportunity for increased efficiency is in improved use of the mechanical energy (usually in the form of fluids or solid materials in motion) in the process. Comprehensive programs to address motor-system energy use start with the process and work back toward the power line, optimizing each element in turn, as well as the overall system. Outlining such a program is beyond the scope of this discussion; see (e.g.) Baldwin 1989 for an example of the benefits that propagate all the way back to the power plant.

11.2.1 Motor Efficiency

Figure 11.4 shows the distribution of the losses of an induction motor as a function of the load. At low loads the core magnetic losses (hysteresis and eddy currents) are dominant, whereas at higher loads the copper resistive ("Joule" or I^2R) losses are the most important. Mechanical losses are also present in the form of friction in the bearings and windage.

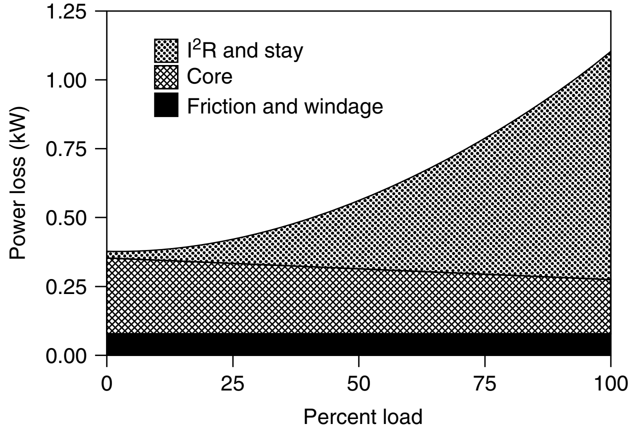

FIGURE 11.4 Variation of losses with load for a 10 hp motor. (Reprinted from *Energy-Efficient Motor Systems: A Handbook on Technology, Program and Policy Opportunities*, 1992, American Council for an Energy Efficient Economy, Washington, D.C. With permission.)

11.2.1.1 Energy-Efficient and Premium-Efficiency Motors

After World War II and until the early 1970s, there was a trend to design inefficient motors which minimized the use of raw materials (copper, aluminum, and silicon steel). These induction motors had lower initial costs and were more compact than previous generations of motors, but their running costs were higher. When electricity prices started escalating rapidly in the mid-1970s, most of the large motor manufacturers added a line of higher-efficiency motors to their selection. Such motors feature optimized design, more generous electrical and magnetic circuits and higher quality materials (Baldwin 1989). Incremental efficiency improvements are still possible with the use of superior materials (e.g., amorphous silicon steel) and optimized computer-aided design techniques.

In 1997, the U.S. Energy Policy Act (EPAct) put in place mandatory efficiency standards for many general-purpose motors. Also in the 1990s, the Consortium for Energy Efficiency (CEE) developed a voluntary premium-efficiency standard, which evolved into the NEMA Premium designation (NEMA 2000; Nadel et al. 2002). Premium efficiency motors offer an efficiency improvement over EPAct which typically ranges from 4% for a 1 hp motor, to 2% for a 150 hp motor, as shown in Figure 11.5. Due to long motor lives, many motors in use are less efficient than EPAct, and thus there is an even larger difference between them and premium efficiency motors. Premium efficiency motors normally cost around 15%–25% more than standard motors, which translates into a price premium of $8-40/hp. In new applications, and for motors with a large number of operating hours, the paybacks are normally under 4 years for Premium vs. EPAct motors, and under 2 years for Premium vs. older, standard-efficiency motors.

11.2.1.2 Efficiency of Rewound Motors

When a motor fails, the user has the options of having the motor rebuilt, buying a new EPAct motor, or buying a NEMA Premium motor. Except for large motors with low annual operating hours, it is typically very cost-effective to replace the failed motor with a Premium motor. Although motor rebuilding is a low-cost alternative, the efficiency of a rebuilt motor can be substantially decreased by the use of improper methods for stripping the old winding. On average, the efficiency of a motor decreases by about 1% each time the motor is rewound.

The use of high temperatures (above 350°C) can damage the interlaminar insulation and distort the magnetic circuit with particular impact on the air gap shape, leading to substantially higher core and stray losses. Before any motor is rewound, it should be checked for mechanical damage and the condition

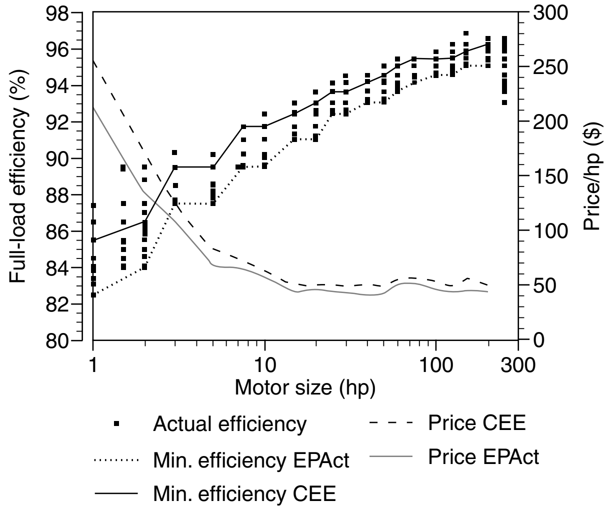

FIGURE 11.5 Ranges for full-load efficiency vs. size, and costs (average per hp trade prices) vs. size for NEMA Design B standard and high-efficiency, 1,800 rpm, three-phase induction motors. Distribution of efficiency data points reflects variation among manufacturers. EPAct and CEE premium-efficiency and minimum-efficiency values are provided for reference. Price per hp values is based on average price for qualifying product in the *MotorMaster* database. (Reprinted from *Energy-Efficient Motor Systems: A Handbook on Technology, Program and Policy Opportunities*, 2002, American Council for an Energy-Efficient Economy, Washington, D.C. With permission.)

of the magnetic circuit should be tested with an electronic iron core loss meter. There are techniques available to remove the old windings, even the ones coated with epoxy varnish, which do not exceed 350°C (Dreisilker 1987).

11.2.2 Recent Motor Developments

In the low horsepower range, the induction motor is being challenged by new developments in motor technology such as permanent magnet and reluctance motors which are as durable as induction motors and have higher efficiency. These advanced motors do not have losses in the rotor and feature higher torque and power/weight ratio. In fractional hp motors, such as the ones used in home appliances, the efficiency improvements can reach 10%–15%, compared with single-phase induction motors. Compared to the shaded-pole motors commonly used in small fans, improved motor types can more than double motor efficiency.

11.2.2.1 Permanent-Magnet Motors

Over the last few decades, there has been substantial progress in the area of permanent-magnet materials. Figure 11.6 shows the relative performance of several families of magnetic materials. High-performance permanent-magnet materials such as neodymium–iron–boron alloys, with a large energy density and moderate cost, offer the possibility of achieving high efficiency and compact light-weight motors.

In modern designs, the permanent magnets are used in the rotor. The currents in the stator windings are switched by semiconductor power devices based on the position of the rotor, normally detected by Hall sensors, as shown in Figure 11.7. The rotor rotates in synchronism with the rotating magnetic field created by the stator coils, leading to the possibility of accurate speed control. Because these motors have no brushes, and with suitable control circuits they can be fed from a DC supply, they are sometimes called brushless DC motors.

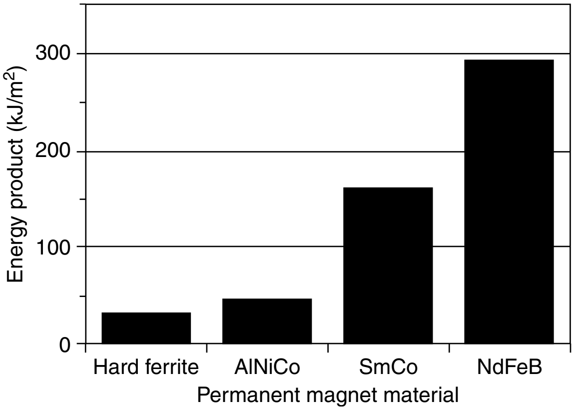

FIGURE 11.6 The evolution of permanent-magnet materials, showing the increasing magnetic energy density ("energy product"). Ferrites were developed in the 1940s; AlNiCos (aluminum, nickel, and cobalt) in the 1930s. The rare-earth magnets were developed beginning in the 1960s (samarium–cobalt) and in the 1980s (neodymium–iron–boron). The higher the energy density, the more compact the motor design can be for a given power rating. (Reprinted from *Energy-Efficient Motor Systems: A Handbook on Technology, Program and Policy Opportunities*, 1992, American Council for an Energy Efficient Economy, Washington, D.C. With permission.)

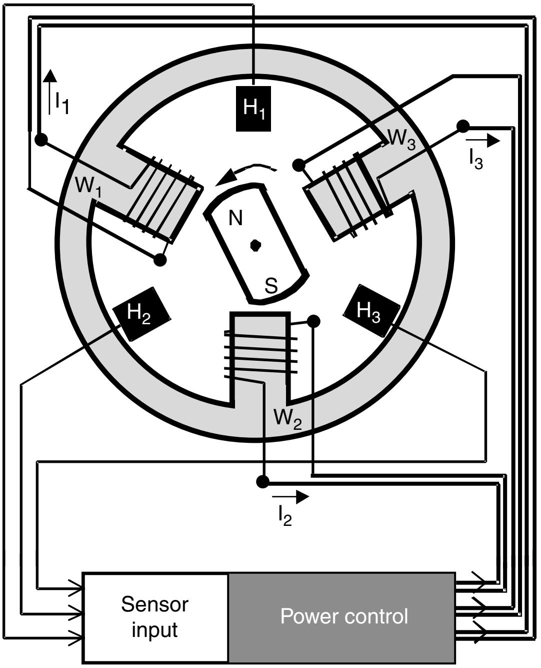

FIGURE 11.7 Control system scheme of a brushless DC motor. This motor is also known as an electronically commutated permanent-magnet (PM) motor. The motor is composed of three sets of stator windings arranged around the permanent-magnet rotor. AC power is first converted to DC, and then switched to the windings by the power control unit, which responds to both an external speed command and rotor position feedback from H_1, H_2, and H_3, which are magnetic position sensors. If a DC power supply is available, it can be used directly by the power control unit in place of the AC supply and converter. The function of the commutator and brushes in the conventional DC motor is replaced by the control unit and power switches. The PM rotor follows the rotating magnetic field created by the stator windings. The speed of the motor is easily changed by varying the frequency of switching.

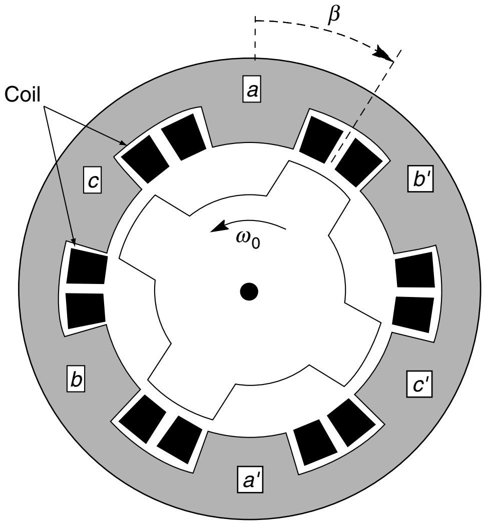

FIGURE 11.8 Schematic view of a switched reluctance motor. The configuration shown is a 6/4 pole. A rotating magnetic field is produced by switching power on and off to the stator coils in sequence, thus magnetizing poles a–a′, b–b′, and c–c′ in sequence. Switching times are controlled by microprocessors with custom programming.

11.2.2.2 Switched Reluctance Motors

Switched reluctance motors are also synchronous motors whose stator windings are commutated by semiconductor power switches to create a rotating field. The rotor has no windings, being made of iron with salient poles. The rotor poles are magnetized by the influence of the stator rotating field. The attraction between the magnetized poles and the rotating field creates a torque that keeps the rotor moving at synchronous speed. Figure 11.8 shows the structure of a switched reluctance motor.

Switched reluctance motors have higher efficiency than induction motors, are simple to build, robust and, if mass-produced, their price can compete with induction motors. Switched reluctance motors can also be used in high-speed applications (above the 3600 rpm possible with induction or synchronous motors operating on a 60-Hz AC supply) without the need for gears.

11.2.3 Motor Speed Controls

AC induction and synchronous motors are essentially constant-speed motors. Most motor applications would benefit if the speed could be adjusted to the process requirements. This is especially true for new applications where the processes can be designed to take advantage of the variable speed. The potential benefits of speed variation include increased productivity and product quality, less wear in the mechanical components, and substantial energy savings.

In many pump, fan, and compressor applications, the mechanical power grows roughly with the cube of the fluid flow; to move 80% of the nominal flow only half of the power is required. Fluid-flow applications are therefore excellent candidates for motor speed control.

Conventional methods of flow control have used inefficient throttling devices such as valves, dampers and vanes. These devices have a low initial cost, but introduce high running costs due to their inefficiency. Figure 11.9 shows the relative performance of different techniques to control flow produced by a fan.

Motor system operation can be improved through the use of several speed-control technologies, such as those covered in the following three sections.

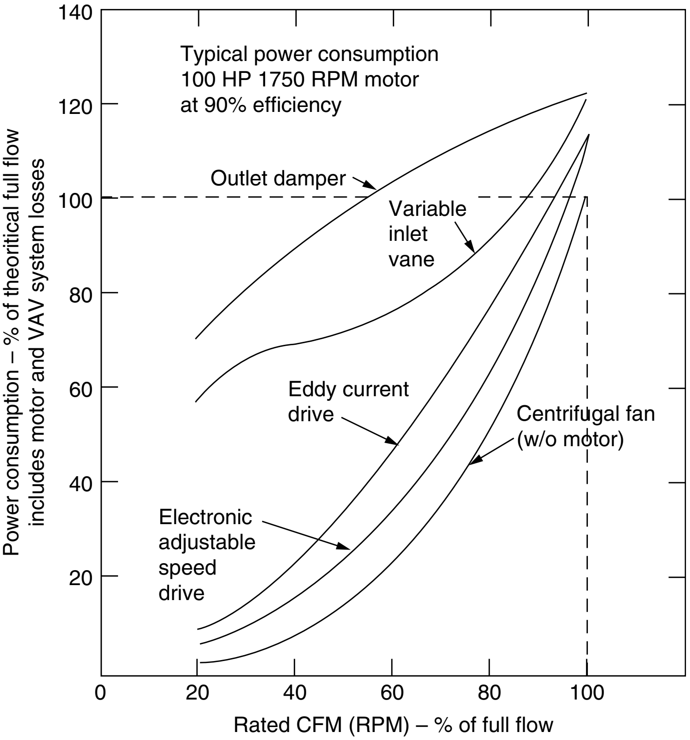

FIGURE 11.9 Comparison of several techniques for varying air flow in a variable-air-volume (VAV) ventilation system. The curve on the lower right represents the power required by the fan itself, not including motor losses. Electronic ASDs are the most efficient VAV control option, offering large savings compared to outlet dampers or inlet vanes, except at high fractions of the rated fan speed. (From Greenberg et al., 1988.)

11.2.3.1 Mechanical and Eddy-Current Drives

Mechanical speed control technologies include hydraulic transmissions, adjustable sheaves, and gearboxes. Eddy-current drives work as induction clutches with controlled slip (Magnusson 1984).

Both mechanical drives and eddy drives have relatively low importance. They suffer from low efficiency, bulkiness, limited flexibility, or limited reliability when compared with other alternatives; in the case of mechanical drives they may require regular maintenance.

Mechanical and eddy drives are not normally used as a retrofit due to their space requirements. Their use is more and more restricted to the low horsepower range where their use may be acceptable due to the possible higher cost of ASDs.

11.2.3.2 Multi-Speed Motors

In applications where only a few operating speeds are required, multi-speed motors may provide the most cost-effective solution. These motors are available with a variety of torque-speed characteristics (variable torque, constant torque, and constant horsepower) (Andreas 1992), to match different types of loads. Two-winding motors can provide up to four speeds but they are normally bulkier (one frame size larger) than single-speed motors for the same horsepower rating. Pole-amplitude modulated (PAM) motors are single winding, two speed, squirrel cage induction motors that provide a wide range of speed ratios (Pastor 1986). Because they use a single winding they have the same frame size of single-speed motors for the same horsepower, and are thus easy to install as a retrofit. PAM motors are available with a broad choice of speed combinations (even ratios close to unity), being especially suited and cost-effective for those fan and pump applications which can be met by a two-speed duty cycle.

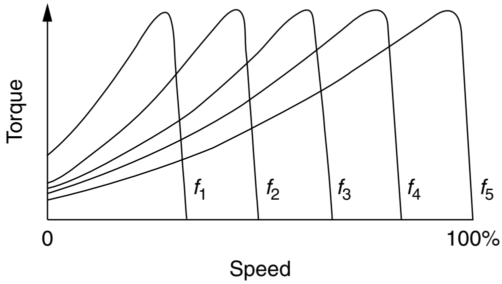

FIGURE 11.10 Speed-torque curves for an induction motor ($f_1 < f_2 < f_3 < f_4 < f_5$, and f_5 = normal line frequency). Normal operation of the motor is in the nearly vertical part of the curves to the right of the “knee” (known as the “breakdown” or “pullout” torque).

11.2.3.3 Electronic Adjustable-Speed Drives

Induction motors operate with a torque-speed relation as shown in Figure 11.10. The speed of the motor is very nearly proportional to the frequency of the AC power supplied to it; thus the speed can be varied by applying a variable-frequency input to the motor. Electronic adjustable-speed drives (ASDs) (Bose 1986) achieve this motor input by converting the fixed frequency power supply (50 or 60 Hz), normally first to a DC supply and then to a continuously variable frequency/variable voltage (Figure 11.11). ASDs are thus able to continuously change the speed of AC motors. Electronic ASDs have no moving parts (sometimes with the exception of a cooling fan), presenting high reliability and efficiency and low maintenance requirements. Because ASDs are not bulky and have flexible positioning requirements, they are generally easy to retrofit.

Electronic ASDs are the dominant motor speed control technology at the present and for the foreseeable future. Developments in the past two decades in the areas of microelectronics and power electronics make possible the design of efficient, compact and increasingly cost-competitive electronic ASDs. As ASDs control the currents/voltages fed to the motor through power semiconductor switches, it is possible to incorporate motor protection features, soft-start and remote control, at a modest cost. By adding additional power switches and controlling circuitry (Figure 11.12), ASDs can provide regenerative braking, slowing the driven load and feeding power back into the AC supply. Such regenerative braking capability can increase the energy efficiency of such applications as elevators, downhill conveyors, and electric transportation.

Across the range of motor applications, no single ASD technology emerges as a clear winner when compared with other ASD types. Pulse-width modulation (PWM) voltage-source inverters ASDs dominate in the low to medium horsepower range (up to several hundred horsepower) due to their lower cost and good overall performance. Figure 11.13 shows how the variable-frequency/variable-voltage waveform is synthesized by a PWM ASD.

In the range above several hundred horsepower the choice of ASD technology depends on several factors including the type of motor, horsepower, speed range and control requirements (Greenberg et al. 1988).

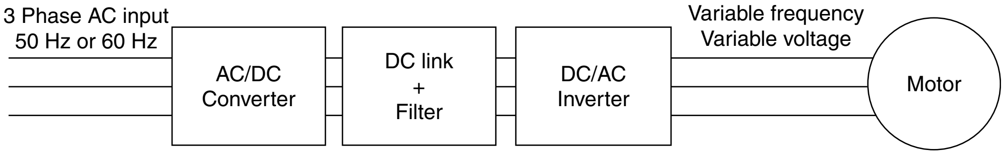

FIGURE 11.11 General inverter based ASD power circuit with motor load.

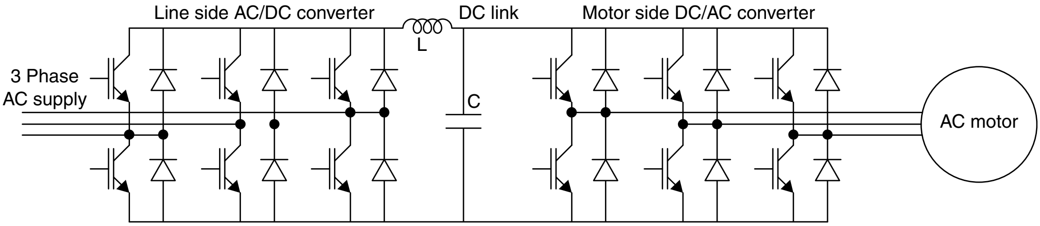

FIGURE 11.12 Power circuitry of a PWM variable speed drive with regenerative capacity and power factor control. Whereas conventional ASDs use diode rectifiers in the input stage, regenerative units use insulated gate bipolar transistors (IGBTs) at both the input and output stages to enable bidirectional power flow.

Table 11.1 presents a general classification of the most widely used adjustable-speed motor drive technologies.

11.2.4 Motor System Oversizing

Motor systems are often oversized as a result of the compounding of successive safety factors in the design of a system (Smeaton 1988). The magnetic losses, friction, and windage losses are practically constant as a function of the load. Therefore, motors which are oversized (working all the time below 50% of capacity) present not only lower efficiency but also poor power factor (NEMA 1999), as shown in Figure 11.14. The efficiency drops significantly when a motor operates lightly loaded (below 40% for a standard motor). The power factor drops continuously from full load. The decrease in performance is especially noticeable in small motors and standard-efficiency motors.

It is therefore essential to size new motors correctly and to identify motors which run grossly underloaded all the time. In the last case, the economics of replacement by a correctly sized motor should be considered. In medium or large industrial plants, where a stock of motors is normally available, oversized motors may be exchanged for the correct size versions.

11.2.5 Power Quality

Electric motors, and in particular induction motors, are designed to operate with optimal performance when fed by symmetrical three-phase sinusoidal waveforms with the nominal voltage value. Deviations from these ideal conditions may cause significant deterioration of the motor efficiency and lifetime. Possible power quality problems include voltage unbalance, undervoltage or overvoltage, and

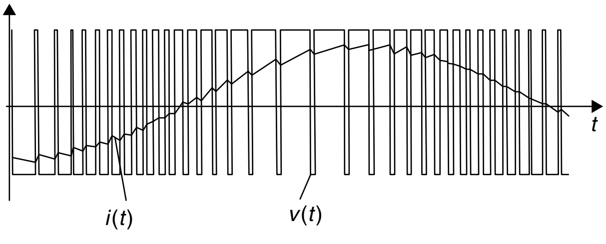

FIGURE 11.13 Pulse-width modulation for synthesizing a sinusoidal output. Output voltage, the average of which resembles the current waveform $i(t)$, is varied by changing the width of the voltage pulses $v(t)$. Output frequency is varied by changing the length of the cycle.

TABLE 11.1 Adjustable-Speed Motor Drive Technologies

Technology	Applicability (R= Retrofit; N= New)	Cost[b]	Comments
		Motors	
Multispeed (incl PAM[a]) motors	Fractional-500 hp PAM; fractional-2,000 + hp R,N	1.5 to 2 times the price of single-speed motors	Larger and less efficient than 1-speed motors. PAM is more promising than multiwinding. Limited number of available speeds.
Direct-current motors	Fractional-10,000 hp N	Higher than AC induction motors	Easy speed control. More maintenance required.
	Shaft-applied drives (on motor output)		
Mechanical			
Variable-ratio belts	5–125 hp N	\$350–\$50/hp (for 5–125 hp)	High efficiency at part load 3:1 speed range limitation. Requires good maintenance for long life.
Friction dry disks	Up to 5 hp N	\$500–\$300/hp	10:1 speed range. Maintenance required.
Hydraulic drive	5–10,000 hp N	Large variation	5:1 speed range. Low efficiency below 50% speed.
Eddy-current drive	Fractional∼2000+ hp N	\$900–\$60/hp (for 1 to 150 hp)	Reliable in clean areas, Relatively long life. Low efficiency below 50% speed.
	Wiring-applied drives (on motor input)		
Electronic adjustable speed drives			
Voltage-source inverter	Fractional-1500 hp R,N	\$300–\$100/hp (for 1 to 300 hp)	Multimotor capability. Can generally use existing motor. PWM[c] appears most promising.
Current-source inverter	100–100,000 hp R,N	\$120–\$50/hp (for 100 to 20,000 hp)	Larger and heavier than VSL Industrial applications, including large synchronous motors.
Others	Fractional-100,000 hp R,N	Large variation	Includes cycloconverters, wound rotor, and variable voltage. Generally for special industrial applications.

[a] PAM means Pole Amplitude Modulated.

[b] The prices are listed from, high to low to correspond with the power rating, which is listed from low to high. Thus, the lower the power rating, the higher the cost per horsepower.

[c] PWM means Pulse Width Modulation.

harmonics and interference. Harmonics and interference can be caused by, as well as affect, motor systems.

11.2.5.1 Voltage Unbalance

Induction motors are designed to operate at their best with three-phase balanced sinusoidal voltages. When the three-phase voltages are not equal, the losses increase substantially. Phase

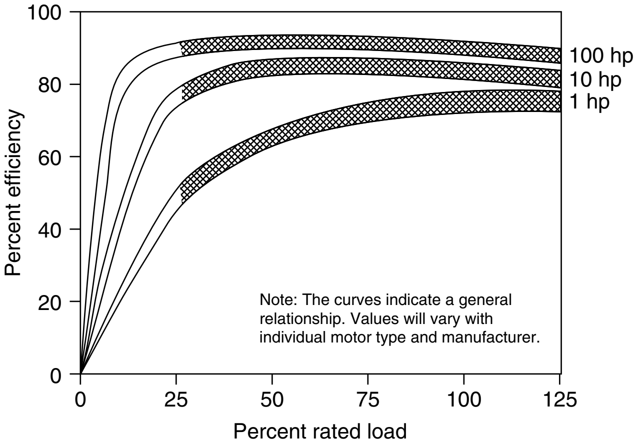

FIGURE 11.14 Typical efficiency vs. load curves for 1800 rpm, three-phase 60 Hz Design B squirrel cage induction motors. (Reprinted from *Energy-Efficient Motor Systems: A Handbook on Technology, Program and Policy Opportunities*, 2002, American Council for an Energy Efficient Economy, Washington, D.C. With permission.)

unbalance is normally caused by an unequal distribution of the single-phase loads (such as lighting) on the three phases or by faulty conditions. An unbalanced supply can be mathematically represented by two balanced systems rotating in opposite directions. The system rotating in the opposite direction to the motor induces currents in the rotor which heat the motor and decrease the torque. Even a modest phase unbalance of 2% can increase the losses by 25% (Cummings, Dunki-Jacobs, and Kerr 1985).

When a phase unbalance is present, the motor must be derated according to Figure 11.15.

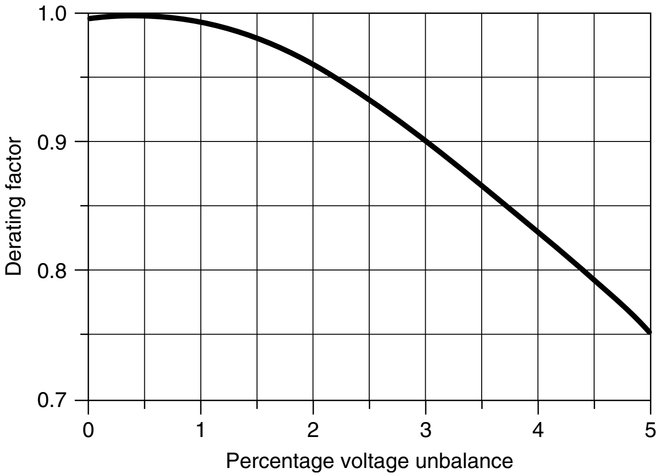

FIGURE 11.15 Derating factor due to unbalanced voltage for integral-horsepower motors. (Reprinted from *Energy-Efficient Motor Systems: A Handbook on Technology, Program and Policy Opportunities*, 1992, American Council for an Energy Efficient Economy, Washington, D.C. With permission.)

11.2.5.2 Voltage Level

When an induction motor is operated above or below its rated voltage, its efficiency and power factor change. If the motor is underloaded, a voltage reduction may be beneficial, but for a properly sized motor the best overall performance is achieved at the rated voltage. The voltage fluctuations are normally associated with ohmic (IR) voltage drops or with reactive power (poor power factor) flow in the distribution network (see Section 11.2.6).

11.2.5.3 Harmonics and Electromagnetic Interference

When harmonics are present in the motor supply, they heat the motor and do not produce useful torque. This in turn affects the motor lifetime and causes a derating of the motor capacity. This is also true when motors are supplied by ASDs which generate the harmonics themselves. The use of premium-efficiency motors can alleviate these problems due to their higher efficiency and thermal capacity; there are also motors specially designed for use with ASDs known as inverter-duty motors.

Reduction of harmonics is also important for the benefit of other consumer and utility equipment. Harmonics, caused by nonlinear loads such as the semiconductor switches in ASDs, should be reduced to an acceptable level as close as possible to the source. The most common technique uses inductive/capacitive filters at the ASD input circuit to provide a shunt path for the harmonics and to perform power factor compensation.

IEEE Standard No. 519 (IEEE 1992) contains guidelines for harmonic control and reactive power compensation of power converters. The cost of the harmonic filter to meet this standard is typically around 5% of the cost of the ASD.

ASD power semiconductor switches operate with fast switching speeds to decrease energy losses. The fast transitions in the waveforms contain high-frequency harmonics, including those in the radio-frequency range. These high-frequency components can produce interference through both conduction and radiation. The best way to deal with EMI is to suppress it at the source. Radiated EMI is suppressed through shielding and grounding of the ASD enclosure. Proper ASD design, the use of a dedicated feeder and the use of a low-pass input filter (an inductor; often called a “line reactor”), will normally suppress conducted EMI.

11.2.6 Distribution Losses

11.2.6.1 Cable Sizing

The currents supplied to the motors in any given installation will produce Joule (I^2R) losses in the distribution cables and transformers of the consumer. Correct sizing of the cables will not only allow a cost-effective minimization of those losses, but also helps to decrease the voltage drop between the transformer and the motor. The use of the National Electrical Code for sizing conductors leads to cable sizes that prevent overheating and allow adequate starting current to the motors, but can be far from an energy-efficient design. For example, when feeding a 100 hp motor located at 150 m from the transformer with a cable sized using NEC, about 4% of the power will be lost in heating the cable (Howe et al. 1999). Considering a 2-year payback, it is normally economical to use a cable one wire size larger than the one required by the NEC.

11.2.6.2 Reactive Power Compensation

In most industrial consumers, the main reason for a poor power factor is the widespread application of oversized motors. Correcting oversizing can thus contribute in many cases to a significant improvement of the power factor.

Reactive power compensation, through the application of correction capacitors, not only reduces the losses in the network but also allows full use of the power capacity of the power system components

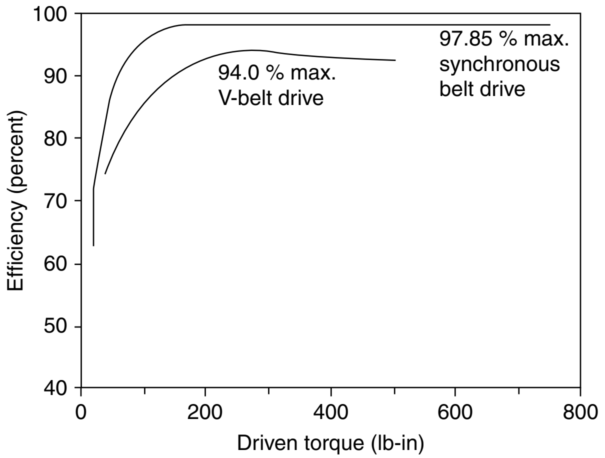

FIGURE 11.16 Efficiency versus torque for V-belts and synchronous belts in a typical application. (Reprinted from *Energy-Efficient Motor Systems: A Handbook on Technology, Program and Policy Opportunities*, 1992, American Council for an Energy Efficient Economy, Washington, D.C. With permission.)

(cables, transformers, circuit breakers, etc.). In addition, voltage fluctuations are reduced, thus helping the motor to operate closer to its design voltage.

11.2.7 Mechanical Transmissions

The transmission subsystem transfers the mechanical power from the motor to the motor-driven equipment. To achieve overall high efficiency it is necessary to use simple, properly maintained transmissions with low losses. The choice of transmission is dependent upon many factors including speed ratio desired, horsepower, layout of the shafts, type of mechanical load, etc.

Transmission types available include direct shaft couplings, gearboxes, chains, and belts. Belt transmissions offer significant potential for savings. About one-third of motor transmissions use belts (Howe et al. 1999). Several types of belts can be used such as V-belts, cogged V-belts and synchronous belts.

V-belts have efficiencies in the 90%–96% range. V-belt losses are associated with flexing, slippage, and a small percentage due to windage. With wear, the V-belt stretches and needs retensioning, otherwise the slippage increases and the efficiency drops. Cogged V-belts have lower flexing losses and have better gripping on the pulleys, leading to 2%–3% efficiency improvement when compared with standard V-belts.

Synchronous belts can be 98%–99% efficient as they have no slippage and have low flexing losses; they typically last over twice as long as V-belts, leading to savings in avoided replacements which more than offset their extra cost. Figure 11.16 shows the relative performance of V-belts and synchronous belts. The efficiency gains increase with light loads.

11.2.8 Maintenance

Regular maintenance (such as inspection, adjustment, cleaning, filter replacement, lubrication, and tool sharpening) is essential to maintain peak performance of the mechanical parts and to extend their operating lifetime. Both under- and over-lubrication can cause higher friction losses in the bearings and shorten the bearing lifetime. Additionally, overgreasing can cause the accumulation of grease and dirt on the motor windings, leading to overheating and premature failure.

The mechanical efficiency of the driven equipment (pump, fan, cutter, etc.) directly affects the overall system efficiency. Monitoring wear and erosion in this equipment is especially important as its efficiency can be dramatically affected. For example, in chemical process industries the erosion of the pump impeller will cause the pump efficiency to drop sharply; a dull cutter will do the same to a machine tool.

Cleaning the motor casing is also relevant because its operating temperature increases as dust and dirt accumulates on the case. The same can be said about providing a cool environment for the motor. The temperature increase leads to an increase of the windings' resistivity and therefore to larger losses. An increase of 25°C in the motor temperature increases the Joule losses by 10%.

11.3 Energy-Saving Applications of ASDs

Typical loads which may benefit from the use of ASDs include those covered in the following four sections.

11.3.1 Pumps and Fans

In many pumps and fans where there are variable-flow requirements, substantial savings can be achieved, as the power is roughly proportional to the cube of the flow (and thus speed of the motor). The use of ASDs instead of throttling valves with pumps shows similar behavior to that for fans in Figure 11.9.

11.3.2 Centrifugal Compressors and Chillers

Air compressors use 16% of all electricity used to power motor driven processes in U.S. industries (XENERGY 1998). Most industrial compressed air systems have significant savings potential. Well-engineered efficiency improvements yield verified savings in the range of 15–30 percent of system energy consumption. See Table 11.2 (Fraunhofer Institute 2000).

Centrifugal compressors and chillers can take advantage of motor controls in the same way as other centrifugal loads (pumps and fans). The use of wasteful throttling devices or the on–off cycling of the equipment can be largely avoided, resulting in both energy savings and extended equipment lifetime.

Savings from compressed air measures are mostly coincident with electric system peak periods. Plant air systems normally have a large load factor, typically operating 5000–8000 h per year. Thus energy and demand reductions are very likely to occur at system peaks and contribute to system reliability. Compressed air system efficiency improvements are highly cost-effective and additionally lead to reduced plant downtime. Many projects have identified significant energy and demand reduction projects with paybacks less than 2 years (XENERGY 2001).

11.3.3 Conveyors

The use of speed controls, in both horizontal and inclined conveyors, allows the matching of speed to material flow. As the conveyor friction torque is constant, energy savings are obtained when the conveyor is operated at reduced speed. In long conveyors, such as found in power plants and in the mining industry, the benefits of soft-start without the need for complex auxiliary equipment are also significant (De Almeida, Ferreira, and Both 2005).

For horizontal conveyors (Figure 11.17), the torque is approximately independent of the transported load (it is only friction-dependent). Typically, the materials handling output of a conveyor is controlled through the regulation of input quantity, and the torque and speed are roughly constant. But, if the materials input to the conveyor is changed, it is possible to reduce the speed (the torque is the same), and, as it can be seen in Figure 11.18, significant energy savings will be reached, proportional to the speed reduction.

TABLE 11.2 Energy Savings Measures for Compressed-Air Systems

Energy Savings Measure	% Applicability[a]	% Gains[b]	Potential Contribution[c] (%)	Comments
		System Installation or Renewal		
Improvement of drives (high efficiency motors)	25	2	0.5	Most cost-effective in small (< 10 kW) systems
Improvement of drives: (Speed regulation)	25	15	3.8	Applicable to variable load systems. In multi-machine installations, only one machine should be fitted with a variable speed drive. The estimated gain is for overall improvement of systems, be they mono or multi-machine
Upgrading of compressor	30	7	2.1	
Use of sophisticated control systems	20	12	2.4	
Recovering waste heat for use in other functions	20	20	4.0	Note that the gain is in terms of energy, not of electricity consumption, since electricity is converted to useful heat
Improved cooling, drying and filtering	10	5	0.5	This does not include more frequent filter replacement (see below)
Overall system design, including multi-pressure systems	50	9	4.5	
Reducing frictional pressure losses (for example by increasing pipe diameter)	50	3	1.5	
Optimising certain end use devices	5	40	2.0	
		System Operation and Maintenance		
Reducing air leaks	80	20	16.0	Largest potential gain
More frequent filter replacement	40	2	0.8	
Total			32.9	

[a] % of CAS where this measure is applicable and cost-effective

[b] % reduction in annual energy consumption

[c] Potential contribution = applicability × reduction.

11.3.4 High Performance Applications

AC motors have received much attention in recent years as a proposed replacement for DC motors in high-performance speed control applications, where torque and speed must be independently controlled. Induction motors are much more reliable, more compact, more efficient and less expensive than DC

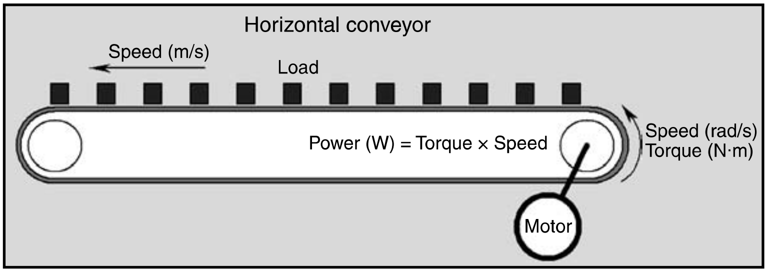

FIGURE 11.17 Power required by a conveyor.

motors. As induction motors have no carbon brush commutation, they are especially suitable for corrosive and explosive environments. In the past, induction motors have been difficult to control as they behave as complex nonlinear systems. However, the appearance on the market of powerful and inexpensive microprocessors has made it possible to implement in real time the complex algorithms required for induction motor control.

Field-oriented control, also called vector control, allows accurate control of the speed and torque of induction motors, in a way similar to DC motor control (Leonhard 1984). The motor current and voltage waveforms, together with motor position feedback, are processed in real time, allowing the motor current to be decomposed into a field producing component and into a torque producing component. Vector control operation principle is represented in Figure 11.19 and is being applied to a wide variety of high-performance applications described next.

Rolling mills were one of the strongholds of DC motors, due to the accurate speed and torque requirements. With present ASD technology, AC drives can outperform DC drives in all technical aspects (reliability, torque/speed performance, maximum power, efficiency), and are capable of accurate control down to zero speed.

The availability of large diameter, high torque, and low speed AC drives makes them suitable for use in applications like ball mills and rotary kilns without the need for gearboxes. This area was also a stronghold of DC drives. Again, AC drives have the capability to offer superior performance in terms of reliability, power density, overload capability, efficiency, and dynamic characteristics.

AC traction drives can also feature regenerative braking. AC traction drives are already being used in trains, rapid transit systems, ship propulsion and are the proper choice for the electric automobile.

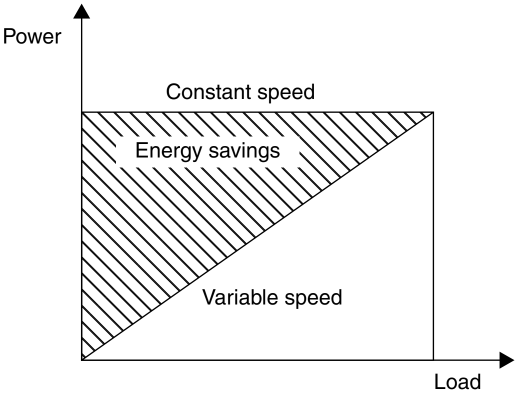

FIGURE 11.18 Energy savings in a conveyor using speed control, in relation to the typical constant speed.

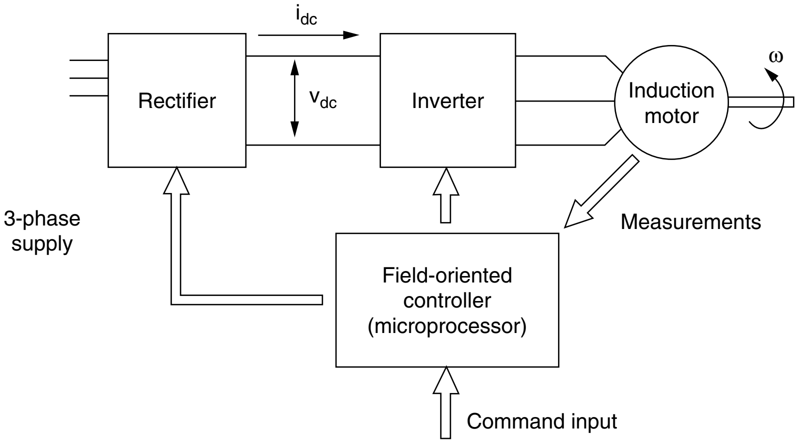

FIGURE 11.19 Schematic of a vector-control drive (also known as a field-oriented control). (Reprinted from *Energy-Efficient Motor Systems: A Handbook on Technology, Program and Policy Opportunities*, 1992, American Council for an Energy Efficient Economy, Washington, D.C. With permission.)

DC drives have traditionally been used with winders in the paper and steel industry in order to achieve the constant tension requirements as the winding is performed. Sometimes the constant tension is obtained by imposing friction, which wastes energy. AC drives can also be used to replace DC drives, saving energy and achieving better overall performance.

The use of field-oriented AC drives in machine tools and robotics allows the stringent requirements regarding dynamic performance to be met. Positioning drives can produce a peak torque up to 10 times the rated torque and make possible the adjustment of the speed to very low values.

In machine tools, AC drives can provide accurate higher spindle speeds than DC drives without the need for gearboxes and their associated losses. The ASDs can also adjust the voltage level when the spindle drive is lightly loaded, providing further savings. In robotics, the higher power density and superior dynamics of AC drives are important advantages.

11.4 Energy and Power Savings Potential; Cost-Effectiveness

The energy and peak power savings potential for any motor-related technology depends on a number of factors, including the characteristics of the motor, the motor drive, the driven equipment, and the load (Nadel et al. 2002). Since all of this information is seldom available, it is difficult to determine the effect of even a single application; it is far more difficult to determine the savings potential for diverse applications, across all sectors, for an entire nation.

This section estimates the energy and power savings that could be realized nationwide in the U.S. through the application of these technologies in the residential, commercial, industrial, and utility sectors. Table 11.3 lists the major motor-driven end uses, estimates of their energy use as a percentage of total national electricity use (based on Howe et al. (1999) and Nadel et al. (2002)) and the potential energy savings from ASDs expressed as a fraction of existing use.

11.4.1 Potential Savings in the Residential Sector

About 38% of residential electricity is used in motor systems. The primary motor technology for realizing energy and power savings in the residential sector is the electronic adjustable-speed drive (ASD). Heat pumps, air conditioners, forced-air furnaces and washing machines with ASDs have already been

TABLE 11.3 Electric Motor Usage and Potential ASD Savings by Sector and End Use

Sector	End Use	Usage (% of Total U.S. Usage)	Potential ASD Savings (% of Usage for Each End Use)
Residential	Refrigeration	3.0	10
	Space heating	2.1	20
	Air conditioning	3.4	15
	HVAC Dist. Fan	1.8	25
	Other	1.6	5
	Residential total	11.9	15
Commercial	Refrigeration	2.2	10
	HVAC compressors	3.3	15
	HVAC distribution	4.2	25
	Other	0.7	20
	Commercial total	10.4	18
Industrial	Refrigeration	1.5	10
	Pumps	5.7	20
	Fans	3.2	20
	Compressed air	3.6	15
	Material handling	2.8	15
	Material process	5.2	15
	Other	1.0	0
	Industrial total	23.1	16
Utilities	Pumps and fans	4.9	15
	Material handling and processing	2.2	15
	Utilities total	7.1	19

introduced into the market. Other appliances, such as refrigerators, freezers, heat pump water heaters and evaporative coolers, are also potential candidates for adjustable-speed controls. Most of the energy-saving potential of ASDs in the home is associated with the use of refrigerant compressors for cooling or heating (as in heat pumps, air conditioners, refrigerators, and freezers). In all of these applications, ASDs can reduce energy consumption by matching the speed of the compressor to the instantaneous thermal load. Given the assumed savings potential, the overall savings is about 15% of the sector's motor electricity.

Several improvements in home appliance technology that are likely to become common over the next few years will complement the use of ASDs:

- High-efficiency compressor and fan motors. The use of permanent-magnet and reluctance motors can increase the efficiency of the motor by 5%–15%, when compared with conventional squirrel-cage single-phase induction motors; as noted above, even larger savings are possible with many small fan motors. Permanent-magnet AC motors are used in the latest ASD-equipped furnace and heat pump.
- Rotary and scroll compressors. The use of rotary (in small applications) or scroll compressors in place of reciprocating compressors can take full advantage of the speed variation potential of ASDs.
- Larger heat exchangers with improved design. Improved heat exchangers increase the efficiency by decreasing the temperature difference of the compressor thermal cycle.

11.4.2 Potential Savings in the Commercial Sector

An estimated 37% of commercial electricity use is for motor-driven end uses (Howe et al. 1999); the percentage for peak power is higher. The savings potential of ASDs in air-conditioning and ventilation applications was estimated by running DOE-2 computer simulations on two representative building types in five U.S. cities (Eto and de Almeida 1988). Comparisons were made between the cooling and ventilation systems with and without ASDs. The results indicate ventilation savings of approximately 25% for energy and 6% for peak power, and cooling savings of about 15% and 0%, respectively. In Table 11.3 we assumed these energy results can be applied nation-wide.

The estimated 10% energy savings for refrigeration are shown in Table 11.3; an estimated 5% savings in peak power should also be attainable. Other motor efficiency measures (discussed in Section 11.2) combined, can capture approximately 10% more energy and demand savings, with an overall potential savings of about 18% of the sector's motor system electricity.

11.4.3 Potential Savings in the Industrial and Utility Sectors

About 70% of industrial and 89% of the utility sector electricity use is for motor systems. In Table 11.3, the fluid moving end use savings are estimated at 20%, except for utilities, where the system requirements of municipal water works limit the savings. Compressed air and materials applications are assumed to have 15% potential.

As most industries are nonseasonal, with flat load profiles during operating hours, the peak savings are similar to energy savings. When other motor efficiency measures (see Section 11.2) are combined, approximately 10% more energy and demand savings can be obtained, resulting in a total of 16% combined savings for the motor systems in these sectors.

Installed Cost ($/hp)	Size Range (hp)
300–180	7.5–50
180–120	50–200
120–100	200–1000
100–60	1000–2500
60–50	2500–20,000

11.4.4 Cost-Effectiveness of ASDs

The price of ASD equipment, in terms of dollars/horsepower, is a function of the horsepower range, the type of AC motor used, and the additional control and protection facilities offered by the electronic ASD. ASD installation costs vary tremendously depending on whether the application is new or retrofit, available space, weather protection considerations, labor rates, etc. Thus there is a huge range of installed costs possible for any given ASD size, and the costs listed below necessarily have large uncertainties.

A market survey (De Almeida et al. 2001), showed the following typical dollar values for equipment and installation of drives for induction motors (the higher $/hp in each range corresponds to the small end of the hp range):

These numbers are graphically presented in their original units of Euros and kW in Figure 11.20.

Mass production of smaller motors with built-in ASDs has been very successful in bringing down the cost of Japanese variable-speed heat pumps, with reported incremental costs of $25/hp for the ASD (Abbate 1988).

To determine whether an ASD is cost-effective for any given application, the following need to be taken into account:

- First cost (acquisition and installation)
- System operating load profile (number of hours per year at each level of load)
- Cost of electricity

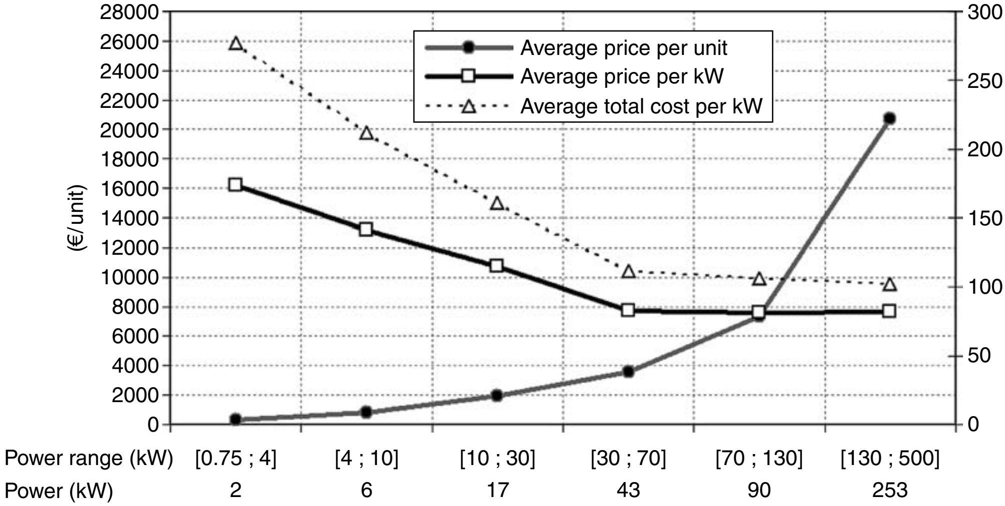

FIGURE 11.20 Average unit costs and average per kW costs, for the different power ranges in the European Union (1 Euro = 1.2 U.S.$, August 2005); 1 kW of power range = 1.3 hp.

- Maintenance requirements
- Reliability
- Secondary benefits (less wear on equipment, less operating noise, regeneration capability, improved control, soft-start, and automatic protection features)
- Secondary problems (power factor, harmonics, and interference)

A careful analysis should weigh the value of the benefits offered by each option against the secondary problems, such as power quality, that may impose extra costs for filters and power factor correction capacitors.

Comparing the cost of conserved energy to the cost of electricity is a crude way to assess the cost-effectiveness of energy efficiency measures. More accurate calculations would account for the time at which conservation measures save energy relative to the utility system peak demand, and relate these "load shape characteristics" to baseload, intermediate and peaking supply resources. See Koomey, Rosenfeld, and Gadgil (1990a, 1990b) for more details.

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12

Energy Storage Technologies

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12.1 Overview of Storage Technologies

Energy storage will play a critical role in an efficient and renewable energy future; much more so than it does in today's fossil-based energy economy. There are two principal reasons that energy storage will grow in importance with increased development of renewable energy:

- Many important renewable energy sources are intermittent, and generate when weather dictates, rather than when energy demand dictates.
- Many transportation systems require energy to be carried with the vehicle.[1]

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[1] This is almost always true for private transportation systems, and usually untrue for public transportation systems, which can rely on rails or overhead wires to transmit electric energy. However, some public transportation systems such as buses do not have fixed routes and also require portable energy storage.

Energy can be stored in many forms: as mechanical energy in rotating, compressed, or elevated substances; as thermal or electrical energy waiting to be released from chemical bonds; or as electrical charge ready to travel from positive to negative poles on demand.

Storage media that can take and release energy in the form of electricity have the most universal value, because electricity can efficiently be converted either to mechanical or heat energy, whereas other energy conversion processes are less efficient. Electricity is also the output of three of the most promising renewable energy technologies: wind turbines, solar thermal, and photovoltaics. Storing this electricity in a medium that naturally accepts electricity is favored, because converting the energy to another type usually has a substantial efficiency penalty.

Still, some applications can benefit from mechanical or thermal technologies. Examples are when the application already includes mechanical devices or heat engines that can take advantage of the compatible energy form; lower environmental impacts that are associated with mechanical and thermal technologies; or low cost resulting from simpler technologies or efficiencies of scale.

In this chapter, the technologies are grouped into five categories: direct electric, electrochemical, mechanical, direct thermal, and thermochemical. Table 12.1 is a summary of all of the technologies covered. Each is listed with indicators of appropriate applications that are further explained in Section 12.3.

TABLE 12.1 Overview of Energy Storage Technologies and Their Applications

	Utility Shaping	Power Quality	Distributed Grid	Automotive
Direct electric				
Ultracapacitors		✓		✓
SMES		✓		
Electrochemical				
Batteries				
Lead–acid	✓	✓	✓	
Lithium-ion	✓	✓	✓	✓
Nickel–cadmium	✓	✓		
Nickel–metal hydride				✓
Zebra				✓
Sodium–sulfur	✓	✓		
Flow Batteries				
Vanadium redox	✓			
Polysulfide bromide	✓			
Zinc bromide	✓			
Electrolytic hydrogen				✓
Mechanical				
Pumped hydro	✓			
Compressed air	✓			
Flywheels		✓		✓
Direct Thermal				
Sensible Heat				
Liquids			✓	
Solids			✓	
Latent Heat				
Phase change	✓		✓	
Hydration–dehydration	✓			
Chemical reaction	✓		✓	
Thermochemical				
Biomass solids	✓		✓	
Ethanol	✓			✓
Biodiesel				✓
Syngas	✓			✓

All technologies are discussed in this chapter except hydrogen-based solutions.

12.2 Principal Forms of Stored Energy

The storage media discussed in this chapter can accept and deliver energy in three fundamental forms: electrical, mechanical, and thermal. Electrical and mechanical energy are both considered high-quality energy because they can be converted to either of the other two forms with fairly little energy loss (e.g., electricity can drive a motor with only about 5% energy loss, or a resistive heater with no energy loss).

The quality of thermal energy storage depends on its temperature. Usually, thermal energy is considered low quality because it cannot be easily converted to the other two forms. The theoretical maximum quantity of useful work $W_{\max}$ (mechanical energy) extractable from a given quantity of heat Q is

$$W_{\max} = \frac{T_1 - T_2}{T_1} \times Q,$$

where T_1 is the absolute temperature of the heat and T_2 is the surrounding, ambient absolute temperature.

Any energy storage facility must be carefully chosen to accept and produce a form of energy consistent with either the energy source or the final application. Storage technologies that accept and/or produce heat should, as a rule, only be used with heat energy sources or with heat applications. Mechanical and electric technologies are more versatile, but in most cases electric technologies are favored over mechanical because electricity is more easily transmitted, because there is a larger array of useful applications, and because the construction cost is typically lower.

12.3 Applications of Energy Storage

In Table 12.1 above, each technology is classified by its relevance in one to four different, principal applications:

- *Utility shaping* is the use of very large capacity storage devices to answer electric demand, when a renewable resource is not producing sufficient generation. An example would be nighttime delivery of energy generated by a solar thermal plant during the prior day.
- *Power quality* is the use of very responsive storage devices (capable of large changes in output over very short timescales) to smooth power delivery during switching events, short outages, or plant run-up. Power-quality applications can be implemented at central generators, at switchgear locations, and at commercial and industrial customers' facilities. Uninterruptible power supplies (UPS) are an example of this category.
- *Distributed grid technologies* enable energy generation and storage at customer locations, rather than at a central (utility) facility. The distributed grid is an important, enabling concept for photovoltaic technologies that are effective at a small scale and can be installed on private homes and commercial buildings. When considered in the context of photovoltaics, the energy storage for the distributed grid is similar to the utility shaping application in that both are solutions to an intermittent, renewable resource, but distributed photovoltaic generation requires small capacities in the neighborhood of a few tens of MJ, while utility shaping requires capacities in the TJ range.[2] Renewable thermal resources (solar, geothermal) can also be implemented on a distributed scale, and require household-scale thermal storage tanks. For the purposes of this chapter, district-heating systems are also considered a distributed technology.

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[2] Storage capacities in this chapter are given in units of MJ, GJ, and TJ: 1 MJ = 0.28 kWh, 1 GJ = 280 kWh, and 1 TJ = 280 MWh.

- *Automotive applications* include battery-electric vehicles (EVs), hybrid gasoline–electric vehicles, plug-in hybrid electric vehicles (PHEVs), and other applications that require mobile batteries larger than those used in today's internal combustion engine cars. A deep penetration of automotive batteries also could become important in a distributed grid. Large fleets of EVs or PHEVs that are grid connected when parked would help enable renewable technologies, fulfilling utility shaping and distributed grid functions as well as their basic automotive function.

Additional energy storage applications exist, most notably portable electronics and industrial applications. However, the four applications described here make up the principal components that will interact in a significant way with the global energy grid.

12.4 Specifying Energy Storage Devices

Every energy storage technology, regardless of category, can be roughly characterized by a fairly small number of parameters. Self-discharge time, unit size, and efficiency serve to differentiate the various categories. Within a category, finer selections of storage technology can be made by paying attention to cycle life, specific energy, specific power, energy density, and power density.

Self-discharge time is the time required for a fully charged, noninterconnected storage device to reach a certain depth of discharge (DOD). DOD is typically described as a percentage of the storage device's useful capacity, so that, for instance, 90% DOD means 10% of the device's energy capacity remains. The relationship between self-discharge time and DOD is rarely linear, so self-discharge times must be measured and compared at a uniform DOD. Acceptable self-discharge times vary greatly, from a few minutes for some power-quality applications, to years for devices designed to shape annual power production.

Unit size describes the intrinsic scale of the technology, and is the least well-defined of the parameters listed here. If the unit size is small compared to the total required capacity of a project, complexity and supply shortages can increase the cost relative to technologies with a larger unit size. Some technologies have a fairly large unit size that prohibits small-scale energy storage.

Figure 12.1 maps all of the technologies discussed in this chapter, according to their unit size and 10% self-discharge time. The gamut of technologies available covers many orders of magnitude on each axis, illustrating the broad choice available. Utility shaping applications require a moderate self-discharge time and a large unit size; power-quality applications are much less sensitive to self-discharge time but require a moderate unit size. Distributed grid and automotive applications both require a moderate self-discharge time and a moderate unit size.

Efficiency is the ratio of energy output from the device, to the energy input. Like energy density and specific energy, the system boundary must be carefully considered when measuring efficiency. It is particularly important to pay attention to the form of energy required at the input and output interconnections, and to include the entire system necessary to attach to those interconnections. For instance, if the system is to be used for shaping a constant-velocity, utility wind farm, then presumably both the input and output will be AC electricity. When comparing a battery with a fuel cell in this scenario, it is necessary to include the efficiencies of an AC-to-DC rectifier for the battery, an AC-powered hydrogen generation system for the fuel cell system, and DC-to-AC converters associated with both systems.

Efficiency is related to self-discharge time. Technologies with a short self-discharge time will require constant charging to maintain a full charge; if discharge occurs much later than charge in a certain application, the apparent efficiency will be lower because a significant amount of energy is lost in maintaining the initial, full charge.

Cycle life is the number of consecutive charge–discharge cycles a storage installation can undergo while maintaining the installation's other specifications within certain, limited ranges. Cycle-life specifications are made against a chosen DOD depending on the application of the storage device.

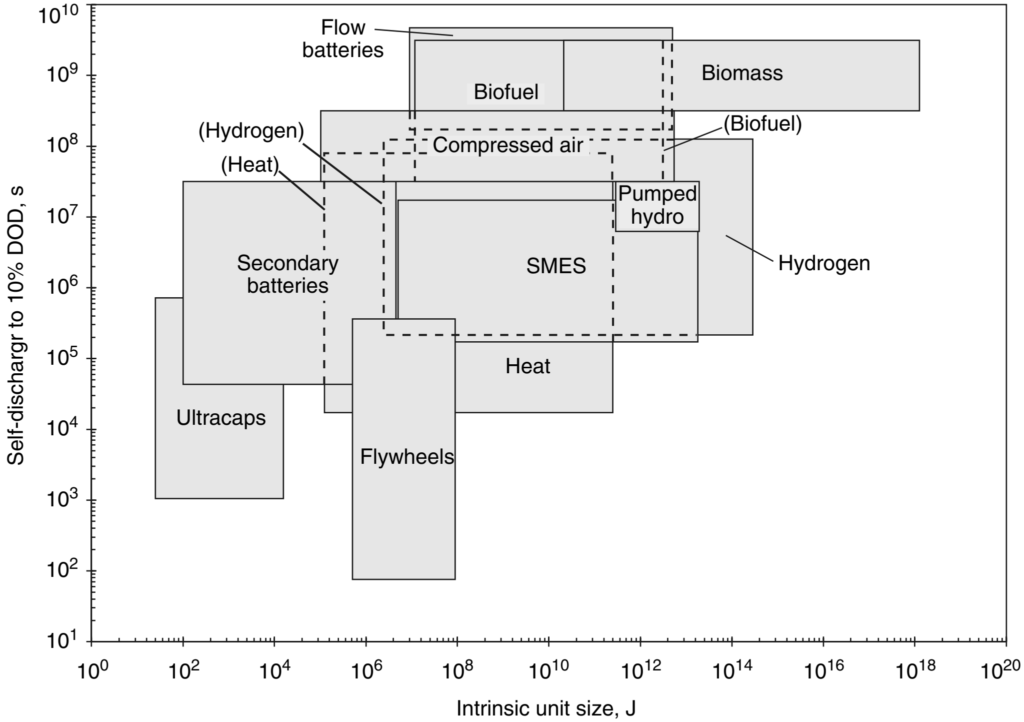

FIGURE 12.1 All storage technologies, mapped by self-discharge time and unit size. Not all hidden lines are shown. Larger self-discharge times are always more desirable, but more or less important depending on the application. Intrinsic unit size does not have a desirability proportional to its value, but rather must be matched to the application.

In some cases, for example pressurized hydrogen storage in automobiles, each cycle will significantly discharge the hydrogen canister and the appropriate DOD reference might be 80% or 90%. In other cases, for example a battery used in a hybrid electric vehicle, most discharge cycles may consume only 10% or 20% of the energy stored in the battery. For most storage technologies, cycle life is significantly larger for shallow discharges than deep discharges, and it is critical that cycle-life data be compared across a uniform DOD assumption.

Specific energy is a measure of how heavy the technology is. It is measured in units of energy per mass, and in this chapter this quantity will always be reported in MJ/kg. The higher the specific energy, the lighter the device. Automotive applications require high specific energies; for utility applications, specific energy is relatively unimportant, except where it impacts construction costs.

Energy density is a measure of how much space the technology occupies. It is measured in units of energy per volume, and in this chapter we will always report this quantity in MJ/L. The higher the energy density, the smaller the device. Again, this is most important for automotive applications, and rarely important in utility applications. Typical values for energy density associated with a few automotive-scale energy technologies are listed in Table 12.2, together with cycle-life and efficiency data.

Energy-density and specific-energy estimates are dependent on the system definition. For example, it might be tempting to calculate the specific energy of a flow battery technology by dividing its capacity by the mass of the two electrolytes. But it is important to also include the mass of the electrolyte storage containers, and of the battery cell for a fair and comparable estimate of its specific energy. Therefore, the energy density and specific energy are dependent on the size of the specific device; large devices benefit from efficiency of scale with a higher energy density and specific energy. *Specific power* and *power density* are the power correlates to specific energy and energy density.

TABLE 12.2 Nominal Energy Density, Cycle Life and Efficiency of Automotive Storage Technologies

	Energy Density MJ/L	Cycle Life at 80% DOD[a]	Electric Efficiency %
Ultracapacitors	0.2	50,000	95
Li-ion batteries	1.8	2,000	85
NiMH batteries	0.6	1,000	80
H_2 at 350 bar	3.0	n/a[b]	47
H_2 at 700 bar	5.0	n/a	45
Air at 300 bar	<0.1	n/a	37
Flywheels	<0.1	20,000	80
Ethanol	23.4	n/a	n/a

Electric efficiencies are calculated for electric-to-electric conversion and momentary storage.

[a] Depth of discharge.

[b] Not applicable.

12.5 Specifying Fuels

A fuel is any (relatively) homogenous substance that can be combusted to produce heat. Though the energy contained in a fuel can always be extracted through combustion, other processes may be used to extract the energy (e.g., reaction in a fuel cell). A fuel may be gaseous, liquid, or solid. All energy storage technologies in the thermochemical category store energy in a fuel. In the electrochemical category, electrolytic hydrogen is a fuel.

A fuel's lower heating value (LHV) is the total quantity of sensible heat released during combustion of a designated quantify of fuel. For example, in the simplest combustion process, that of hydrogen,

$$2\,H_2 + O_2 \rightarrow 2\,H_2O(\text{vapor}) + \text{LHV},$$

or for the slightly more complex combustion of methane,

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O(\text{vapor}) + \text{LHV}.$$

In this chapter, the quantity of fuel is always expressed as a mass, so that LHV is a special case of specific energy. Like specific energy, LHV is expressed in units of MJ/kg in this chapter.

Higher heating value (HHV) is the LHV, plus the latent heat contained in the water vapor resulting from combustion.[3] For the examples of hydrogen and methane, this means

$$2\,H_2 + O_2 \rightarrow 2\,H_2O(\text{liquid}) + \text{HHV},$$

and

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O(\text{liquid}) + \text{HHV}.$$

The latent heat in the water vapor can be substantial, especially for the hydrogen-rich fuels typical in renewable energy applications. Table 12.3 lists LHVs and HHVs of fuels discussed in this chapter; in the most extreme case of molecular hydrogen, the HHV is some 18% higher than the LHV. Recovery of the latent heat requires controlled condensation of the water vapor.

In this chapter, all heating values are reported as HHV rather than LHV. HHV is favored for two reasons: (1) its values allow easier checking of energy calculations with the principle of energy

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[3] The concepts of sensible and latent heat are explained further in Section 12.9.

TABLE 12.3 Properties of Fuels

	Chemical Formula	Density g/L	LHV MJ/kg	HHV MJ/kg
Methanol	CH_3OH	794	19.9	22.7
Ethanol	C_2H_5OH	792	26.7	29.7
Methane	CH_4	0.68	49.5	54.8
Hydrogen	H_2	0.085	120	142
Dry syngas, airless process[a]	$40H_2 + 21CO + 10CH_4 + 29CO_2$	0.89	11.2	12.6
Dry syngas, air process[a]	$25H_2 + 16CO + 5CH_4 + 15CO_2 + 39N_2$	0.99	6.23	7.01

[a] Chemical formulae and associated properties of syngas are representative; actual composition of syngas will vary widely according to manufacturing process.

Source: From All except syngas from U.S. Department of Energy, *Properties of Fuels*, Alternative Fuels Data Center 2004.

conservation, and (2) when examining technologies for future implementation, it is wise to keep an intention of developing methods for extracting as much of each energy source's value as possible.

12.6 Direct Electric Storage

12.6.1 Ultracapacitors

A capacitor stores energy in the electric field between two oppositely charged conductors. Typically, thin conducting plates are rolled or stacked into a compact configuration with a dielectric between them. The dielectric prevents arcing between the plates and allows the plates to hold more charge, increasing the maximum energy storage. The ultracapacitor—also known as supercapacitor, electrochemical capacitor, or electric double layer capacitor (EDLC)—differs from a traditional capacitor in that it employs a thin electrolyte, on the order of only a few angstroms, instead of a dielectric. This increases the energy density of the device. The electrolyte can be made of either an organic or an aqueous material. The aqueous design operates over a larger temperature range, but has a smaller energy density than the organic design. The electrodes are made of a porous carbon that increases the surface area of the electrodes and further increases energy density over a traditional capacitor.

Ultracapacitors' ability to effectively equalize voltage variations with quick discharges make them useful for power-quality management and for regulating voltage in automotive systems during regular driving conditions. Ultracapacitors can also work in tandem with batteries and fuel cells to relieve peak power needs (e.g., hard acceleration) for which batteries and fuel cells are not ideal. This could help extend the overall life and reduce lifetime cost of the batteries and fuel cells used in hybrid and electric vehicles. This storage technology also has the advantage of very high cycle life of greater than 500,000 cycles and a 10- to 12-year life span.[1] The limitations lie in the inability of ultracapacitors to maintain charge voltage over any significant time, losing up to 10% of their charge per day.

12.6.2 Superconducting Magnetic Energy Storage

An superconducting magnetic energy storage (SMES) system is well suited to storing and discharging energy at high rates (high power.) It stores energy in the magnetic field created by direct current in a coil of cryogenically cooled, superconducting material. If the coil were wound using a conventional wire such as copper, the magnetic energy would be dissipated as heat due to the wire's resistance to the flow of current. The advantage of a cryogenically cooled, superconducting material is that it reduces electrical resistance to almost zero. The SMES recharges quickly and can repeat the charge/discharge sequence thousands of times without any degradation of the magnet. A SMES system can achieve full power within 100 ms.[2] Theoretically, a coil of around 150–500 m radius would be able to support a load of 18,000 GJ at

1000 MW, depending on the peak field and ratio of the coil's height and diameter.[3] Recharge time can be accelerated to meet specific requirements, depending on system capacity.

Because no conversion of energy to other forms is involved (e.g., mechanical or chemical), the energy is stored directly and round-trip efficiency can be very high.[2] SMES systems can store energy with a loss of only 0.1%; this loss is due principally to energy required by the cooling system.[3] Mature, commercialized SMES is likely to operate at 97%–98% round-trip efficiency and is an excellent technology for providing reactive power on demand.

12.7 Electrochemical Energy Storage

12.7.1 Secondary Batteries

A secondary battery allows electrical energy to be converted into chemical energy, stored, and converted back to electrical energy. Batteries are made up of three basic parts: a negative electrode, positive electrode, and an electrolyte (Figure 12.2). The negative electrode gives up electrons to an external load, and the positive electrode accepts electrons from the load. The electrolyte provides the pathway for charge to transfer between the two electrodes. Chemical reactions between each electrode and the electrolyte remove electrons from the positive electrode and deposit them on the negative electrode. This can be written as an overall chemical reaction that represents the states of charging and discharging of a battery. The speed at which this chemical reaction takes place is related to the internal resistance that dictates the maximum power at which the batteries can be charged and discharged.

Some batteries suffer from the "memory effect" in which a battery exhibits a lower discharge voltage under a given load than is expected. This gives the appearance of lowered capacity but is actually a voltage depression. Such a voltage depression occurs when a battery is repeatedly discharged to a partial depth and recharged again. This builds an increased internal resistance at this partial depth of discharge and the battery appears as a result to only be dischargeable to the partial depth. The problem, if and when it occurs, can be remedied by deep discharging the cell a few times. Most batteries considered for modern renewable applications are free from this effect, however.

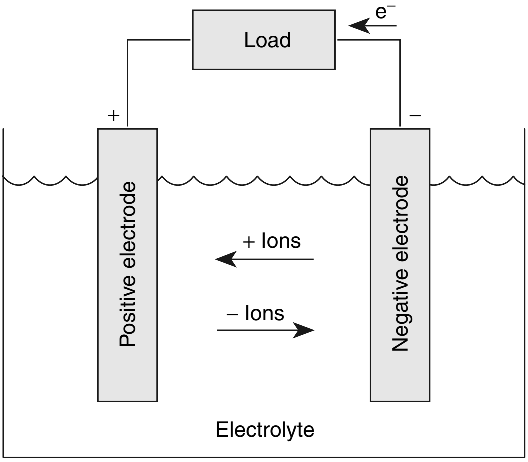

FIGURE 12.2 Schematic of a generalized secondary battery. Directions of electron and ion migration shown are for discharge, so that the positive electrode is the cathode and the negative electrode is the anode. During charge, electrons and ions move in the opposite directions and the positive electrode becomes the anode while the negative electrode becomes the cathode.

12.7.2 Lead–Acid

Lead–acid is one of the oldest and most mature battery technologies. In its basic form, the lead–acid battery consists of a lead (Pb) negative electrode, a lead dioxide (PbO_2) positive electrode and a separator to electrically isolate them. The electrolyte is dilute sulfuric acid (H_2SO_4), which provides the sulfate ions for the discharge reactions. The chemistry is represented by:

$$PbO_2 + Pb + 2\,H_2SO_4 \leftrightarrow 2\,PbSO_4 + 2\,H_2O.$$

(In all battery chemistries listed in this chapter, left-to-right indicates battery discharge and right-to-left indicates charging.)

There are three main types of lead–acid batteries: the flooded cell, the sealed gel cell, and the sealed absorbed glass mat (AGM) lead–acid battery. The wet cell has a liquid electrolyte that must be replaced occasionally to replenish the hydrogen and oxygen that escape during the charge cycle. The sealed gel cell has a silica component added to the electrolyte to stiffen it. The AGM design uses a fiberglass-like separator to hold electrolyte in close proximity to the electrodes, thereby increasing efficiency. For both the gel and AGM configurations, there is a greatly reduced risk of hydrogen explosion and corrosion from disuse. These two types do require a lower charging rate, however. Both the gel cells and the AGM batteries are sealed and pressurized so that oxygen and hydrogen produced during the charge cycle are recombined into water.

The lead–acid battery is a low-cost and popular storage choice for power-quality applications. Its application for utility shaping, however, has been very limited due to its short cycle life. A typical installation survives a maximum of 1500 deep cycles.[4] Yet, lead–acid batteries have been used in a few commercial and large-scale energy management applications. The largest one is a 140-GJ system in Chino, California, built in 1988. Lead–acid batteries have a specific energy of only 0.18 MJ/kg and would therefore not be a viable automobile option apart from providing the small amount of energy needed to start an engine. It also has a poor energy density at around 0.25 MJ/L. The advantages of the lead–acid battery technology are low cost and high power density.

12.7.3 Lithium-Ion

Lithium-ion and lithium polymer batteries, although primarily used in the portable electronics market, are likely to have future use in many other applications. The cathode in these batteries is a lithiated metal oxide ($LiCoO_2$, $LiMO_2$, etc.) and the anode is made of graphitic carbon with a layer structure. The electrolyte consists of lithium salts (such as $LiPF_6$) dissolved in organic carbonates; an example of Li-ion battery chemistry is

$$Li_xC + Li_{1-x}CoO_2 \leftrightarrow LiCoO_2 + C.$$

When the battery is charged, lithium atoms in the cathode become ions and migrate through the electrolyte toward the carbon anode where they combine with external electrons and are deposited between carbon layers as lithium atoms. This process is reversed during discharge. The lithium polymer variation replaces the electrolyte with a plastic film that does not conduct electricity but allows ions to pass through it. The 60°C operating temperature requires a heater, reducing overall efficiency slightly.

Lithium-ion batteries have a high energy density of about 0.72 MJ/L and have low internal resistance; they will achieve efficiencies in the 90% range and above. They have an energy density of around 0.72 MJ/kg. Their high energy efficiency and energy density make lithium-ion batteries excellent candidates for storage in all four applications considered here: utility shaping, power quality, distributed generation, and automotive.

12.7.4 Nickel–Cadmium

Nickel–cadmium (NiCd) batteries operate according to the chemistry:

$$2\,\mathrm{NiOOH} + 2\,\mathrm{H_2O} + \mathrm{Cd} \leftrightarrow 2\,\mathrm{Ni(OH)_2} + \mathrm{Cd(OH)_2}.$$

NiCd batteries are not common for large stationary applications. They have a specific energy of about 0.27 MJ/kg, an energy density of 0.41 MJ/L and an efficiency of about 75%. Alaska's Golden Valley Electric Association commissioned a 40-MW/290-GJ nickel–cadmium battery in 2003 to improve reliability and to supply power for essentials during outages.[5] Resistance to cold and relatively low cost were among the deciding factors for choosing the NiCd chemistry.

Cadmium is a toxic heavy metal and there are concerns relating to the possible environmental hazards associated with the disposal of NiCd batteries. In November 2003, the European Commission adopted a proposal for a new battery directive that includes recycling targets of 75% for NiCd batteries. However, the possibility of a ban on rechargeable batteries made from nickel–cadmium still remains and hence the long-term viability and availability of NiCd batteries continues to be uncertain. NiCd batteries can also suffer from "memory effect," where the batteries will only take full charge after a series of full discharges. Proper battery management procedures can help to mitigate this effect.

12.7.5 Nickel–Metal Hydride

The nickel–metal hydride (Ni*M*H) battery operates according to the chemistry:

$$M\mathrm{H} + \mathrm{NiOOH} \leftrightarrow M + \mathrm{Ni(OH)_2},$$

where M represents one of a large variety of metal alloys that serve to take up and release hydrogen. Ni*M*H batteries were introduced as a higher energy density and more environmentally friendly version of the nickel–cadmium cell. Modern nickel–metal hydride batteries offer up to 40% higher energy density than nickel–cadmium. There is potential for yet higher energy density, but other battery technologies (lithium-ion, in particular) may fill the same market sooner.

Nickel–metal hydride is less durable than nickel–cadmium. Cycling under heavy load and storage at high temperature reduces the service life. Nickel–metal hydride suffers from a higher self-discharge rate than the nickel–cadmium chemistry. Nickel–metal hydride batteries have a specific energy of 0.29 MJ/kg, an energy density of about 0.54 MJ/L and an energy efficiency of about 70%. These batteries have been an important bridging technology in the portable electronics and hybrid automobile markets. Their future is uncertain because other battery chemistries promise higher energy storage potential and cycle life.

12.7.6 Sodium–Sulfur

A sodium–sulfur (NaS) battery consists of a liquid (molten) sulfur positive electrode and liquid (molten) sodium negative electrode, separated by a solid beta-alumina ceramic electrolyte (Figure 12.3). The chemistry is as follows:

$$2\,\mathrm{Na} + x\,\mathrm{S} \leftrightarrow \mathrm{Na_2S}_x.$$

When discharging, positive sodium ions pass through the electrolyte and combine with the sulfur to form sodium polysulfides. The variable x in the equation is equal to 5 during early discharging, but after free sulfur has been exhausted a more sodium-rich mixture of polysulfides with lower average values of x develops. This process is reversible as charging causes sodium polysulfides in the positive electrode to release sodium ions that migrate back through the electrolyte and recombine as elemental sodium. The battery operates at about 300°C. NaS batteries have a high energy density of around 0.65 MJ/L and a specific energy of up to 0.86 MJ/kg. These numbers would indicate an application in the automotive sector, but warm-up time and heat-related accident risk make its use there unlikely. The efficiency of this

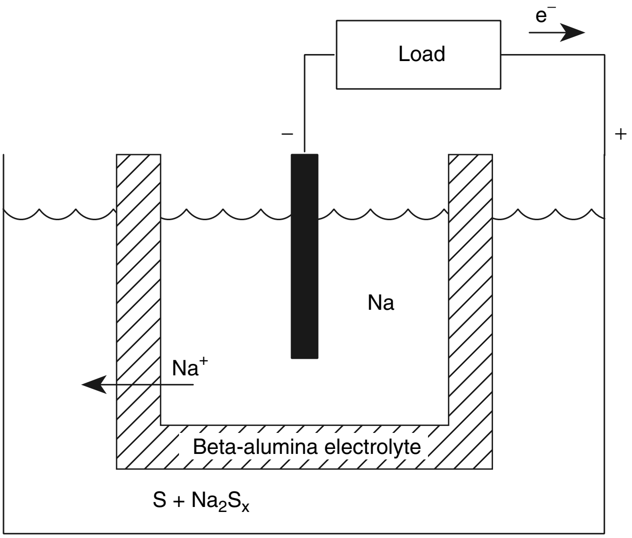

FIGURE 12.3 Sodium–sulfur battery showing discharge chemistry. The sodium (Na) and sulfur (S) electrodes are both in a liquid state and are separated by a solid, beta-alumina ceramic electrolyte that allows only sodium ions to pass. Charge is extracted from the electrolytes with metal contacts; the positive contact is the battery wall.

battery chemistry can be as high as 90% and would be suitable for bulk storage applications while simultaneously allowing effective power smoothing operations.[6]

12.7.7 Zebra

Zebra is the popular name for the sodium–nickel-chloride battery chemistry:

$$NiCl_2 + 2\,Na \leftrightarrow Ni + 2\,NaCl.$$

Zebra batteries are configured similarly to sodium–sulfur batteries (see Figure 12.3), and also operate at about 300°C. Zebra batteries boast a greater than 90% energy efficiency, a specific energy of up to 0.32 MJ/kg and an energy density of 0.49 MJ/L.[7] Its tolerance for a wide range of operating temperature and high efficiency, coupled with a good energy density and specific energy, make its most probable application the automobile sector, and as of 2003 Switzerland's MES-DEA is pursuing this application aggressively.[8] Its high energy efficiency also makes it a good candidate for the utility sector.

12.7.8 Flow Batteries

Most secondary batteries use electrodes both as an interface for gathering or depositing electrons, and as a storage site for the products or reactants associated with the battery's chemistry. Consequently, both energy and power density are tied to the size and shape of the electrodes. Flow batteries store and release electrical energy by means of reversible electrochemical reactions in two liquid electrolytes. An electrochemical cell has two compartments—one for each electrolyte—physically separated by an ion exchange membrane. Electrolytes flow into and out of the cell through separate manifolds and undergo chemical reaction inside the cell, with ion or proton exchange through the membrane and electron exchange through the external electric circuit. The chemical energy in the electrolytes is turned into electrical energy and vice versa for charging. They all work in the same general way but vary in chemistry of electrolytes.[9]

There are some advantages to using the flow battery over a conventional secondary battery. The capacity of the system is scaleable by simply increasing the amount of solution. This leads to cheaper installation costs as the systems get larger. The battery can be fully discharged with no ill effects and has little loss of electrolyte over time. Because the electrolytes are stored separately and in large containers (with a low surface area to volume ratio), flow batteries show promise to have some of the lowest self-discharge rates of any energy storage technology available.

Poor energy densities and specific energies remand these battery types to utility-scale power shaping and smoothing, although they might be adaptable for distributed-generation use. There are three types of flow batteries that are closing in on commercialization: vanadium redox, polysulfide bromide, and zinc bromide.

12.7.8.1 Vanadium Redox

The vanadium redox flow battery (VRB) was pioneered at the University of New South Wales, Australia, and has shown potentials for long cycle life and energy efficiencies of over 80% in large installations.[10] The VRB uses compounds of the element vanadium in both electrolyte tanks. The reaction chemistry at the positive electrode is:

$$V^{5+} + e^{-} \leftrightarrow V^{4+},$$

and at the negative electrode,

$$V^{2+} \leftrightarrow V^{3+} + e^{-}.$$

Using vanadium compounds on both sides of the ion-exchange membrane eliminates the possible problem of cross-contamination of the electrolytes and makes recycling easier.[11] As of 2005, two small, utility-scale VRB installations are operating, one 2.9-GJ unit on King Island, Australia and one 7.2-GJ unit in Castle Valley, Utah.

12.7.8.2 Polysulfide Bromide

The polysulfide bromide battery (PSB) utilizes two salt solution electrolytes, sodium bromide (NaBr) and sodium polysulfide (Na_2S_x). PSB electrolytes are separated in the battery cell by a polymer membrane that only passes positive sodium ions. The chemistry at the positive electrode is

$$NaBr_3 + 2\,Na^{+} + 2\,e^{-} \leftrightarrow 3\,NaBr,$$

and at the negative electrode,

$$2\,Na_2S_2 \leftrightarrow Na_2S_4 + 2\,Na^{+} + 2\,e^{-}.$$

The PSB battery is being developed by Canada's VRB Power Systems, Inc.[12] This technology is expected to attain energy efficiencies of approximately 75%.[13] Although the salt solutions themselves are only mildly toxic, a catastrophic failure by one of the tanks could release highly toxic bromine gas. Nevertheless, the Tennessee Valley Authority released a finding of no significant impact for a proposed 430-GJ facility and deemed it safe.[14]

12.7.8.3 Zinc Bromide

In each cell of a zinc bromide (ZnBr) battery, two different electrolytes flow past carbon-plastic composite electrodes in two compartments separated by a microporous membrane. Chemistry at the positive electrode follows the equation:

$$Br_2(aq) + 2\,e^{-} \leftrightarrow 2\,Br,$$

and at the negative electrode:

$$Zn \leftrightarrow Zn^{2+} + 2e^{-}.$$

During discharge, Zn and Br combine into zinc bromide. During charge, metallic zinc is deposited as a thin-film on the negative electrode. Meanwhile, bromine evolves as a dilute solution on the other side of the membrane, reacting with other agents to make thick bromine oil that sinks to the bottom of the electrolytic tank. During discharge, a pump mixes the bromine oil with the rest of the electrolyte. The zinc bromide battery has an energy efficiency of nearly 80%.[15]

Exxon developed the ZnBr battery in the early 1970 s. Over the years, many GJ-scale ZnBr batteries have been built and tested. Meidisha demonstrated a 1-MW/14-GJ ZnBr battery in 1991 at Kyushu Electric Power Company. Some GJ-scale units are now available preassembled, complete with plumbing and power electronics.

12.7.9 Electrolytic Hydrogen

Diatomic, gaseous hydrogen (H_2) can be manufactured with the process of electrolysis; an electric current applied to water separates it into components O_2 and H_2. The oxygen has no inherent energy value, but the HHV of the resulting hydrogen can contain up to 90% of the applied electric energy, depending on the technology.[16] This hydrogen can then be stored and later combusted to provide heat or work, or to power a fuel cell.

The gaseous hydrogen is low density and must be compressed to provide useful storage. Compression to a storage pressure of 350 bar, the value usually assumed for automotive technologies, consumes up to 12% of the hydrogen's HHV if performed adiabatically, although the loss approaches a lower limit of 5% as the compression approaches an isothermal ideal.[17] Alternatively, the hydrogen can be stored in liquid form, a process that costs about 40% of HHV using current technology, and that at best would consume about 25%. Liquid storage is not possible for automotive applications, because mandatory boil-off from the storage container cannot be safely released in closed spaces (i.e., garages).

Hydrogen can also be bonded into metal hydrides using an absorption process. The energy penalty of storage may be lower for this process, which requires pressurization to only 30 bar. However, the density of the metal hydride can be between 20 and 100 times the density of the hydrogen stored. Carbon nanotubes have also received attention as a potential hydrogen storage medium.[18]

12.8 Mechanical Energy Storage

12.8.1 Pumped Hydro

Pumped hydro is the oldest and largest of all of the commercially available energy storage technologies, with existing facilities up to 1000 MW in size. Conventional pumped hydro uses two water reservoirs, separated vertically. Energy is stored by moving water from the lower to the higher reservoir, and extracted by allowing the water to flow back to the lower reservoir. Energy is stored according to the fundamental physical principle of potential energy. To calculate the stored energy, E_s, in joules, use the formula:

$$E_s = Vdgh,$$

where V is the volume of water raised (m^3), d is the density of water (1000 kg/m^3), g is the acceleration of gravity (9.8 m/s^2), and h is the elevation difference between the reservoirs (m) often referred to as the *head*.

Though pumped hydro is by nature a mechanical energy storage technology, it is most commonly used for electric utility shaping. During off-peak hours electric pumps move water from the lower reservoir to the upper reservoir. When required, the water flow is reversed to generate electricity. Some high dam hydro plants have a storage capability and can be dispatched as pumped hydro storage. Underground pumped storage, using flooded mine shafts or other cavities, is also technically possible but probably prohibitively expensive. The open sea can also be used as the lower reservoir if a suitable upper reservoir can be built at close proximity. A 30-MW seawater pumped hydro plant was first built in Yanbaru, Japan in 1999.

Pumped hydro is most practical at a large scale with discharge times ranging from several hours to a few days. There is over 90 GW of pumped storage in operation worldwide, which is about 3% of global electric generation capacity.[19] Pumped storage plants are characterized by long construction times and high capital expenditure. Its main application is for utility shaping. Pumped hydro storage has the limitation of needing to be a very large capacity to be cost-effective, but can also be used as storage for a number of different generation sites.

Efficiency of these plants has greatly increased in the last 40 years. Pumped storage in the 1960s had efficiencies of 60% compared with 80% for new facilities. Innovations in variable speed motors have helped these plants operate at partial capacity, and greatly reduced equipment vibrations, increasing plant life.

12.8.2 Compressed Air

A relatively new energy storage concept that is implemented with otherwise mature technologies is compressed air energy storage (CAES). CAES facilities must be coupled with a combustion turbine, so are actually a hybrid storage/generation technology.

A conventional gas turbine consists of three basic components: a compressor, combustion chamber, and an expander. Power is generated when compressed air and fuel burned in the combustion chamber drive turbine blades in the expander. Approximately 60% of the mechanical power generated by the expander is consumed by the compressor supplying air to the combustion chamber.

A CAES facility performs the work of the compressor separately, stores the compressed air, and at a later time injects it into a simplified combustion turbine. The simplified turbine includes only the combustion chamber and the expansion turbine. Such a simplified turbine produces far more energy than a conventional turbine from the same fuel, because there is potential energy stored in the compressed air. The fraction of output energy beyond what would have been produced in a conventional turbine is attributable to the energy stored in compression.

The net efficiency of storage for a CAES plant is limited by the heat energy loss occurring at compression. The overall efficiency of energy storage is about 75%.[20]

CAES compressors operate on grid electricity during off-peak times, and use the expansion turbine to supply peak electricity when needed. CAES facilities cannot operate without combustion because the exhaust air would exit at extremely low temperatures causing trouble with brittle materials and icing. If 100% renewable energy generation is sought, biofuel could be used to fuel the gas turbines. There might still be other emissions issues but the system could be fully carbon neutral.

The compressed air is stored in appropriate underground mines, caverns created inside salt rocks or possibly in aquifers. The first commercial CAES facility was a 290-MW unit built in Hundorf, Germany in 1978. The second commercial installation was a 110-MW unit built in McIntosh, Alabama in 1991. The third commercial CAES is a 2,700-MW plant under construction in Norton, Ohio. This nine-unit plant will compress air to about 100 bar in an existing limestone mine 2200 ft. (766 m) underground.[21] The natural synergy with geological caverns and turbine prime movers dictate that these be on the utility scale.

12.8.3 Flywheels

Most modern flywheel energy storage systems consist of a massive rotating cylinder (comprised of a rim attached to a shaft) that is supported on a stator by magnetically levitated bearings that eliminate bearing wear and increase system life. To maintain efficiency, the flywheel system is operated in a low vacuum environment to reduce drag. The flywheel is connected to a motor/generator mounted onto the stator that, through some power electronics, interact with the utility grid.

The energy stored in a rotating flywheel, in joules, is given by

$$E = \frac{1}{2} I \omega^2$$

where I is the flywheel's moment of inertia (kg m^2), and ω is its angular velocity (s^{-2}). I is proportional to the flywheel's mass, so energy is proportional to mass and the square of speed. In order to maximize energy capacity, flywheel designers gravitate toward increasing the flywheel's maximum speed rather than increasing its moment of inertia. This approach also produces flywheels with the higher specific energy.

Some of the key features of flywheels are low maintenance, a cycle life of better than 10,000 cycles, a 20-year lifetime and environmentally friendly materials. Low-speed, high-mass flywheels (relying on I for energy storage) are typically made from steel, aluminum, or titanium; high-speed, low-mass flywheels (relying on ω for energy storage) are constructed from composites such as carbon fiber.

Flywheels can serve as a short-term ride-through before long-term storage comes online. Their low energy density and specific energy limit them to voltage regulation and UPS capabilities. Flywheels can have energy efficiencies in the upper 90% range depending on frictional losses.

12.9 Direct Thermal Storage

Direct thermal technologies, although they are storing a lower grade of energy (heat, rather than electrical or mechanical energy) can be useful for storing energy from systems that provide heat as a native output (e.g., solar thermal, geothermal), or for applications where the energy's commodity value is heat (e.g., space heating, drying).

Although thermal storage technologies can be characterized by specific energy and energy density like any other storage technology, they can also be characterized by an important, additional parameter: the delivery temperature range. Different end uses have more or less allowance for wide swings of the delivery temperature. Also, some applications require a high operating temperature that only some thermal storage media are capable of storing.

Thermal storage can be classified into two fundamental categories: sensible heat storage and latent heat storage. Applications that have less tolerance for temperature swings should utilize a latent heat technology.

Input to and output from heat energy storage is accomplished with heat exchangers. The discussion below focuses on the choice of heat storage materials; the methods of heat exchange will vary widely depending on properties of the storage material, especially its thermal conductivity. Materials with higher thermal conductivity will require a smaller surface area for heat exchange. For liquids, convection or pumping can reduce the need for a large heat exchanger. In some applications, the heat exchanger is simply the physical interface of the storage material with the application space (e.g., phase-change drywall, see below).

12.9.1 Sensible Heat

Sensible heat is the heat that is customarily and intuitively associated with a change in temperature of a massive substance. The heat energy, E_s, stored in such a substance is given by:

$$E_s = (T_2 - T_1) c M,$$

where c is the specific heat of the substance (J/kg °C) and M is the mass of the substance (kg); T_1 and T_2 are the initial and final temperatures, respectively (°C). The specific heat c is a physical parameter measured in units of heat per temperature per mass: substances with the ability to absorb heat energy with a relatively small increase in temperature (e.g., water) have a high specific heat, whereas those that get hot with only a little heat input (e.g., lead) have a low specific heat. Sensible heat storage is best accomplished with materials having a high specific heat.

12.9.1.1 Liquids

Sensible heat storage in a liquid is, with very few exceptions, accomplished with water. Water is unique among chemicals in having an abnormally high specific heat of 4,186 J/kg K, and furthermore has a reasonably high density. Water is also cheap and safe. It is the preferred choice for most nonconcentrating solar thermal collectors.

Liquids other than water may need to be chosen if the delivery temperature must be higher than 100°C, or if the system temperature can fall below 0°C. Water can be raised to temperatures higher than 100°C, but the costs of storage systems capable of containing the associated high pressures are usually prohibitive. Water can be mixed with ethylene glycol or propylene glycol to increase the useful temperature range and prevent freezing.

When a larger temperature range than that afforded by water is required, mineral, synthetic, or silicone oils can be used instead. The tradeoffs for the increased temperature range are higher cost, lower specific heat, higher viscosity (making pumping more difficult), flammability, and, in some cases, toxicity.

For very high temperature ranges, salts are usually preferred that balance a low specific heat with a high density and relatively low cost. Sodium nitrate has received the most prominent testing for this purpose in the U.S. Department of Energy's Solar Two Project located in Barstow, California.

Liquid sensible heat storage systems are strongly characterized not just by the choice of heat-transfer fluid, but also by the system architecture. Two-tank systems store the cold and hot liquids in separate tanks (Figure 12.4). Thermocline systems use a single tank with cold fluid entering or leaving the bottom of the tank and hot fluid entering or leaving the top (Figure 12.5). Thermocline systems can be particularly low cost because they minimize the required tank volume, but require careful design to prevent mixing of the hot and cold fluid.

One particularly interesting application of the thermocline concept is nonconvecting, salinity-gradient solar ponds that employ the concept in reverse. Solar ponds are both an energy collection and energy storage technology. Salts are dissolved in the water to introduce a density gradient, with the densest (saltiest) water on the bottom and lightest (freshest) on top. Solar radiation striking the dark bottom of the pond heats the densest water, but convection of the heated water to the top cannot occur because the density gradient prevents it. Salinity-gradient ponds can generate and store hot water at temperatures approaching 95°C.[22]

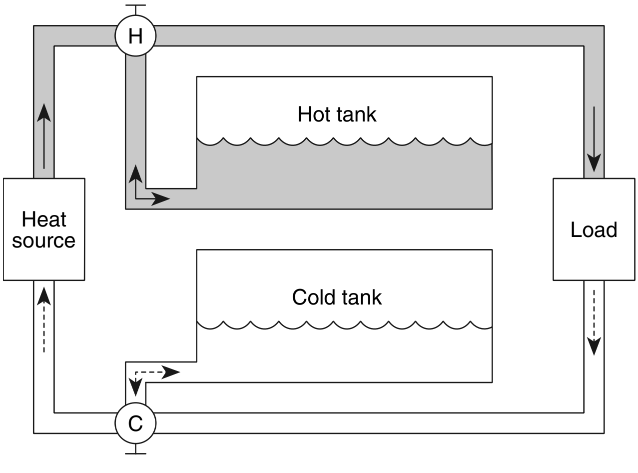

FIGURE 12.4 Two-tank thermal storage system; hot water is shown in gray and cold water is shown in white. When the heat source is producing more output than required for the load, valve H is turned to deposit hot liquid in the tank. When it is producing less than required for the load, the valve is turned to provide supplemental heat from the storage tank. Note that each tank must be large enough to hold the entire fluid capacity of the system.

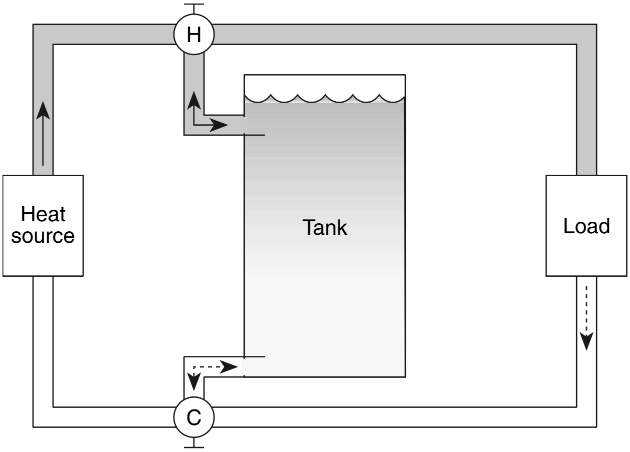

FIGURE 12.5 Thermocline storage tank. Thermocline storage tanks are tall and narrow to encourage the gravity-assisted separation of hot and cold fluid, and include design features (especially at the input/output connectors) to prevent mixing in the stored fluid.

12.9.1.2 Solids

Storage of sensible heat in solids is usually most effective when the solid is in the form of a bed of small units, rather than a single mass. The reason is that the surface-to-volume ratio increases with the number of units, so that heat transfer to and from the storage device is faster for a greater number of units. Energy can be stored or extracted from a thermal storage bed by passing a gas (such as air) through the bed. Thermal storage beds can be used to extract and store the latent heat of vaporization from water contained in flue gases.

Although less effective for heat transfer, monolithic solid storage has been successfully used in architectural applications and solar cookers.

12.9.2 Latent Heat

Latent heat is absorbed or liberated by a phase change or a chemical reaction and occurs at a constant temperature. A phase change means the conversion of a homogenous substance among its various solid, liquid, or gaseous phases. One very common example is boiling water on the stovetop: though a substantial amount of heat is absorbed by the water in the pot, the boiling water maintains a constant temperature of 100°C. The latent heat, E_s, stored through a phase change is:

$$E_s = lM,$$

where M is the mass of material undergoing a phase change (kg), and l is the latent heat of vaporization (for liquid–gas phase changes) or the latent heat of fusion (for solid–liquid phase changes), in J/kg; l is measured in units of energy per mass. Conservation of energy dictates that the amount of heat absorbed in a given phase change is equal to the amount of heat liberated in the reverse phase change.

Although the term *phase change* is used here to refer only to straightforward freezing and melting, many sources use the term *phase-change materials* or *PCMs* to refer to any substance storing latent heat (including those described in Section 12.9.2.2 and Section 12.9.2.3, as well.)

12.9.2.1 Phase Change

Practical energy storage systems based on a material phase change are limited to solid–solid and solid–liquid phase changes. Changes involving gaseous phases are of little interest due to the expense associated with containing a pressurized gas, and difficulty of transferring heat to and from a gas.

Solid–solid phase changes occur when a solid material reorganizes into a different molecular structure in response to temperature. One particularly interesting example is lithium sulfate (Li_2SO_4) which undergoes a change from a monoclinic structure to a face-centered cubic structure at 578°C, absorbing 214 J/g in the process, more than most solid–liquid phase changes.[23]

Some common chemicals, their melting points and heats of fusion are listed in Table 12.4. Fatty acids and paraffins received particular attention in the 1990s as candidate materials for the heat storage component of phase-change drywall, a building material designed to absorb and release heat energy near room temperature for the purpose of indoor temperature stabilization.[24] In this application, solids in the drywall maintain the material's structural integrity even though the phase-change materials are transitioning between solid and liquid states.

12.9.2.2 Hydration–Dehydration

In this process, a salt or similar compound forms a crystalline lattice with water below a "melting-point" temperature, and at the melting point the crystal dissolves in its own water of hydration. Sodium sulfate (Na_2SO_4) is a good example, forming a lattice with ten molecules of water per molecule of sulfate ($Na_2SO_4 \cdot 10H_2O$) and absorbing 241 J/g at 32°C.[25]

Hydration–dehydration reactions have not found significant application in renewable energy systems, although they, too, have been a candidate for phase-change drywall.

12.9.2.3 Chemical Reaction

A wide variety of reversible chemical reactions are available that release and absorb heat (see, for example, Hanneman, Vakil, and Wentorf[26]). The principal feature of this category of latent heat storage technologies is the ability to operate at extremely high temperatures, in some cases over 900°C. Extremely high temperature applications have focused primarily on fossil and advanced nuclear applications; to date, none of these chemical methods of heat storage have been deployed in commercial renewable energy applications.

TABLE 12.4 Melting Points and Heats of Fusion for Solid–Liquid Phase Changes

	Melting Point°C	Heat of Fusion J/g
Aluminum bromide	97	42
Aluminum iodide	191	81
Ammonium bisulfate	144	125
Ammonium nitrate	169	77
Ammonium thiocyanate	146	260
Anthracine	96	105
Arsenic tribromide	32	37
Beeswax	62	177
Boron hydride	99	267
Metaphosphoric acid	43	107
Naphthalene	80	149
Naphthol	95	163
Paraffin	74	230
Phosphoric acid	70	156
Potassium	63	63
Potassium thiocyanate	179	98
Sodium	98	114
Sodium hydroxide	318	167
Sulfur	110	56
Tallow	76	198
Water	0	335

Source: From Kreith, F. and Kreider J.F., *Principles of Solar Engineering*, Taylor & Francis, 1978. With permission

12.10 Thermochemical Energy Storage

This section provides an overview of biomass storage technologies from an energetic perspective only.

12.10.1 Biomass Solids

Plant matter is a storage medium for solar energy. The input mechanism is photosynthesis conversion of solar radiation into biomass. The output mechanism is combustion of the biomass to generate heat energy.

Biologists measure the efficiency of photosynthetic energy capture with the metric net primary productivity (NPP), which is usually reported as a yield in units similar to dry Mg/ha-yr (dry metric tons per hectare per year). However, to enable comparisons of biomass with other solar energy storage technologies, it is instructive to estimate a solar efficiency by multiplying the NPP by the biomass heating value (e.g., MJ/dry Mg) and then dividing the result by the average insolation at the crop's location (e.g., MJ/ha-yr). The solar efficiency is a unitless value describing the fraction of incident solar energy ultimately available as biomass heating value. Most energy crops capture between 0.2 and 2% of the incident solar energy in heating value of the biomass; Table 12.5 shows examples of solar efficiencies estimated for a number of test crops.

TABLE 12.5 Primary Productivity and Solar Efficiency of Biomass Crops

Location	Crop	Yield (dry Mg/ha-yr)	Average Insolation (W/m^2)	Solar Efficiency(%)
Alabama	Johnsongrass	5.9	186	0.19
Alabama	Switchgrass	8.2	186	0.26
Minnesota	Willow and hybrid poplar	8–11	159	0.30–0.41
Denmark	Phytoplankton	8.6	133	0.36
Sweden	Enthropic lake angiosperm	7.2	106	0.38
Texas	Switchgrass	8–20	212	0.22–0.56
California	*Euphorbia lathyris*	16.3–19.3	212	0.45–0.54
Mississippi	Water hyacinth	11.0–33.0	194	0.31–0.94
Texas	Sweet sorghum	22.2–40.0	239	0.55–0.99
Minnesota	Maize	24.0	169	0.79
West Indies	Tropical marine angiosperm	30.3	212	0.79
Israel	Maize	34.1	239	0.79
Georgia	Subtropical saltmarsh	32.1	194	0.92
Congo	Tree plantation	36.1	212	0.95
New Zealand	Temperate grassland	29.1	159	1.02
Marshall Islands	Green algea	39.0	212	1.02
New South Wales	Rice	35.0	186	1.04
Puerto Rico	*Panicum maximum*	48.9	212	1.28
Nova Scotia	Sublittoral seaweed	32.1	133	1.34
Colombia	Pangola grass	50.2	186	1.50
West Indies	Tropical forest, mixed ages	59.0	212	1.55
California	Algae, sewage pond	49.3–74.2	218	1.26–1.89
England	Coniferous forest, 0–21 years	34.1	106	1.79
Germany	Temperate reedswamp	46.0	133	1.92
Holland	Maize, rye, two harvests	37.0	106	1.94
Puerto Rico	*Pennisetum purpurcum*	84.5	212	2.21
Hawaii	Sugarcane	74.9	186	**2.24**
Java	Sugarcane	86.8	186	2.59
Puerto Rico	Napier grass	106	212	2.78
Thailand	Green algae	164	186	4.90

Source: From Klass, D. L., Biomass for Renewable Energy, Fuels, and Chemicals, Academic Press, San Diego, CA, 1998. With permission.

The principal method for extracting useful work or electricity from biomass solids is combustion. Therefore, the solar efficiencies listed in Table 12.5 need to be multiplied by the efficiency of any associated combustion process to yield a net solar efficiency. For example, if a boiler-based electric generator extracts 35% of the feedstock energy as electricity, and the generator is sited at a switchgrass plantation achieving 0.30% solar capture efficiency on a mass basis, the electric plant has a net solar efficiency of 0.30% × 35% = 0.11%. Because biomass is a low-efficiency collector of solar energy, it is very land intensive compared to photovoltaic or solar thermal collectors that deliver energy at solar efficiencies over 20%. However, the capacity of land to store standing biomass over time is extremely high, with densities up to several hundred Mg/ha (and therefore several thousand GJ/ha), depending on the forest type. Standing biomass can serve as long-term storage, although multiple stores need to be used to accommodate fire risk. For short-term storage, woody biomass may be dried, and is frequently chipped or otherwise mechanically treated to create a fine and homogenous fuel suitable for burning in a wider variety of combustors.

12.10.2 Ethanol

Biomass is a more practical solar energy storage medium if it can be converted to liquid form. Liquids allow for more convenient transportation and combustion, and enable extraction on demand (through reciprocating engines) rather than through a less dispatchable, boiler- or turbine-based process. This latter property also enables its use in automobiles.

Biomass grown in crops or collected as residue from agricultural processes consists principally of cellulose, hemicellulose, and lignin. The sugary or starchy by-products of some crops such as sugarcane, sugar beet, sorghum, molasses, corn, and potatoes can be converted to ethanol through fermentation processes, and these processes are the principal source of ethanol today. Starch-based ethanol production is low efficiency, but does succeed in transferring about 16% of the biomass heating value to the ethanol fuel.[27]

When viewed as a developing energy storage technology, ethanol derived from cellulose shows much more promise than the currently prevalent starch-based ethanol.[28] Cellulosic ethanol can be manufactured with two fundamentally different methods: either the biomass is broken down to sugars using a hydrolysis process, and then the sugars are subjected to fermentation; or the biomass is gasified (see below), and the ethanol is subsequently synthesized from this gas with a thermochemical process. Both processes show promise to be far cheaper than traditional ethanol manufacture via fermentation of starch crops, and will also improve energy balances. For example, it is estimated that dry sawdust can yield up to 224 L/Mg of ethanol, thus recovering about 26% of the higher heating value of the sawdust.[29] Because the ethanol will still need to be combusted in a heat engine, the gross, biomass-to-useful-work efficiency will be well below this. In comparison, direct combustion of the biomass to generate electricity makes much more effective use of the biomass as an energy storage medium. Therefore, the value of ethanol as an energy storage medium lies mostly in the convenience of its liquid (rather than solid) state.

12.10.3 Biodiesel

As starch-based ethanol is made from starchy by-products, most biodiesel is generated from oily by-products. Some of the most common sources are rapeseed oil, sunflower oil, and soybean oil. Biodiesel yields from crops like these range from about 300 to 1000 kg/ha-yr, but the crop as a whole produces about 20 Mg/ha-yr, meaning that the gross solar capture efficiency for biodiesel from crops ranges between 1/20 and 1/60 the solar capture efficiency of the crop itself. Because of this low solar-capture efficiency, biomass cannot be the principal energy storage medium for transportation needs.[30]

Biodiesel can also be manufactured from waste vegetable or animal oils; however, in this case, the biodiesel is not functioning per se as a solar energy storage medium, so is not further treated in this work.

12.10.4 Syngas

Biomass can be converted to a gaseous state for storage, transportation, and combustion (or other chemical conversion).[31] Gasification processes are grouped into three different classes: *pyrolysis* is the application of heat in anoxic conditions; *partial oxidation* is combustion occurring in an oxygen-starved environment; *reforming* is the application of heat in the presence of a catalyst. All three processes form syngas, a combination of methane, carbon monoxide, carbon dioxide and hydrogen. The relative abundances of the gaseous products can be controlled by adjusting heat, pressure, and feed rates. The HHV of the resulting gas can contain up to 78% of the original HHV of the feedstock, if the feedstock is dry.[29] Compositions and heating values of two example syngases are listed in Table 12.3.

The equivalent of up to 10% of the gas HHV will be lost when the gas is pressurized for transportation and storage. Even with this loss, gasification is a considerably more efficient method than ethanol manufacture for transferring stored solar energy to a nonsolid medium.

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13

Demand-Side Management

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13.1 Introduction

Since the mid-1980s, demand-side management has been an important element of the electric utility planning approach referred to as “integrated resource planning.” At that time, annual demand-side management expenditures in the U.S. were measured in billions of dollars, energy savings were measured in billions of kilowatts hours, and peak load reductions were stated in thousands of megawatts. Although activities nationally have slowed since then, there are a number of instances where demand-side management continued to influence the demand for electricity. This article defines demand-side management, describes the role demand-side management plays in integrated resource planning, and discusses the main elements of demand-side management programs. It then presents case studies of four successful demand-side management programs that were offered between 2001 and 2003.

13.2 What is Demand-Side Management?

The term *demand-side management* is the result of a logical evolution of planning processes used by utilities in the late 1980s. One of the first terms, *demand-side load management* was introduced by the author, Clark W. Gellings, in an article for IEEE's *Spectrum* in 1981. Shortly after the publication of this article, at a meeting of The Edison Electric Institute (EEI) Customer Service and Marketing Executives in 1982, Mr. Gellings altered the term to *demand-side planning*. This change was made to reflect the broader objectives of the planning process. Mr. Gellings coined the term *demand-side management* and continued to popularize the term throughout a series of more than 100 articles since that time, including the five-volume set *Demand-Side Management* that is widely recognized as a definitive and practical source of information on the demand-side management process.

Perhaps the most widely accepted definition of demand-side management is the following: "Demand-side management is the planning, implementation, and monitoring of those utility activities designed to influence customer use of electricity in ways that will produce desired changes in the utility's load shape, i.e., changes in the time pattern and magnitude of a utility's load. Utility programs falling under the umbrella of demand-side management include: load management, new uses, strategic conservation, electrification, customer generation, and adjustments in market share" (Gellings 1984–1988). However, demand-side management is even more encompassing than this definition implies because it includes the management of all forms of energy at the demand-side, not just electricity. In addition, groups other than just electric utilities (including natural gas suppliers, government organizations, nonprofit groups, and private parties) implement demand-side management programs.

In general, demand-side management embraces the following critical components of energy planning:

1. Demand-side management will influence customer use. Any program intended to influence the customer's use of energy is considered demand-side management.
2. Demand-side management must achieve selected objectives. To constitute a "desired load shape change," the program must further the achievement of selected objectives, i.e., it must result in reductions in average rates, improvements in customer satisfaction, achievement of reliability targets, etc.
3. Demand-side management will be evaluated against non-demand-side management alternatives. The concept also requires that selected demand-side management programs further these objectives to at least as great an extent as non-demand-side management alternatives, such as generating units, purchased power or supply-side storage devices. In other words, it requires that demand-side management alternatives be compared to supply-side alternatives. It is at this stage of evaluation that demand-side management becomes part of the integrated resource planning process.
4. Demand-side management identifies how customers will respond. Demand-side management is pragmatically oriented. Normative programs ("we ought to do this") do not bring about the desired result; positive efforts ("if we do this, that will happen") are required. Thus, demand-side management encompasses a process that identifies how customers will respond not how they should respond.
5. Demand-side management value is influenced by load shape. Finally, this definition of demand-side management focuses upon the load shape. This implies an evaluation process that examines the value of programs according to how they influence costs and benefits throughout the day, week, month, and year.

Subsets of these activities have been referred to in the past as "load management," "strategic conservation," and "marketing."

13.3 Demand-Side Management and Integrated Resource Planning

A very important part of the demand-side management process involves the consistent evaluation of demand-side to supply-side alternatives and vice versa. This approach is referred to as "integrated resource planning." Figure 13.1 illustrates how demand-side management fits into the integrated

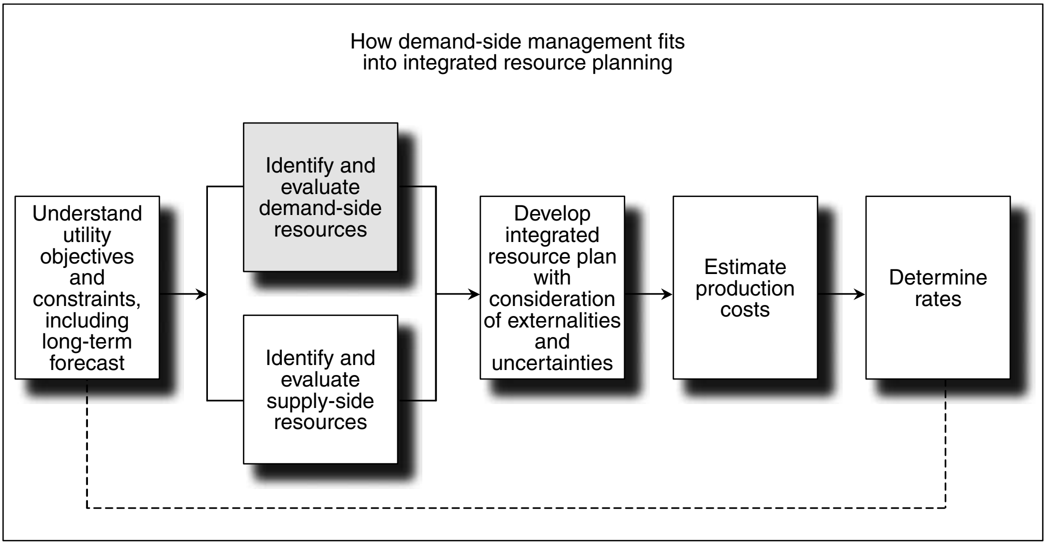

FIGURE 13.1 How demand-side management fits into integrated resources planning.

resource planning process. For demand-side management to be a viable resource option, it has to compete with traditional supply-side options.

13.4 Demand-Side Management Programs

A variety of programs have been implemented since the introduction of demand-side management in the early 1980s. Mr. Gellings and EPRI have been instrumental in defining a framework for utilities and other implementers to follow when planning demand-side management programs. This section describes the main elements of the demand-side management planning framework. It then discusses the types of end use sectors, buildings, and end use technologies targeted during program development. It also lists the various entities typically responsible for implementing programs, along with several program implementation methods. Lastly, this section summarizes several representative demand-side management programs offered in the US.

13.4.1 Elements of the Demand-Side Management Planning Framework

Figure 13.2 illustrates the five main elements of the demand-side management planning framework. These five elements are summarized as follows:

1. Set objectives. The first step in demand-side management planning is to establish overall organizational objectives. These strategic objectives are quite broad and generally include examples, such as reducing energy needs, reducing dependence on foreign imports, improving cash flow, increasing earnings, or improving customer and employee relations. The second level of the formal planning process is to operationalize broad objectives to guide policymakers to specific actions. It is at this operational level or tactical level that demand-side management alternatives should be examined and evaluated. For example, an examination of capital investment requirements may show periods of high investment needs. Postponing the need for new construction through a demand-side management program may reduce investment needs and stabilize the financial future of an energy company, or a utility and its state or country. Specific operational

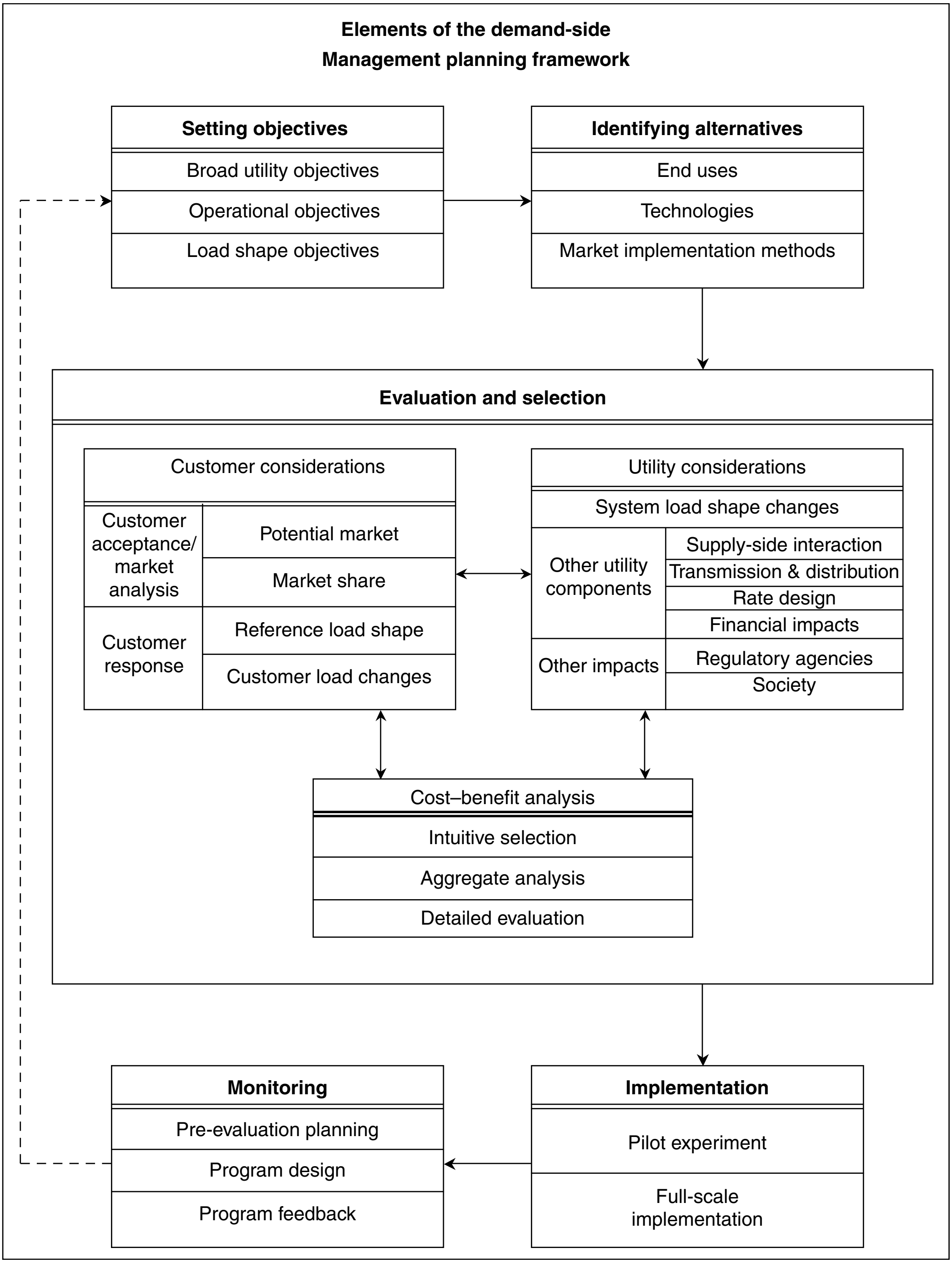

FIGURE 13.2 Elements of the demand-side management planning framework.

objectives are established on the basis of the conditions of the existing energy system—its system configuration, cash reserves, operating environment, and competition. Once designated, operational objectives are translated into desired demand-pattern changes or load-shape changes that can be used to characterize the potential impact of alternative demand-side management programs. Although there is an infinite combination of load-shape-changing possibilities, six have been illustrated in Figure 13.3 to show the range of possibilities, namely peak clipping, valley filling, load shifting, strategic conservation, strategic load growth, and flexible load shape. These six are not mutually exclusive, and may frequently be employed in combinations.

2. Identify alternatives. The second step is to identify alternatives. The first dimension of this step involves identifying the appropriate end uses whose peak load and energy consumption characteristics generally match the requirements of the load-shape objectives established in the previous step. In general, each end use (e.g., residential space heating, commercial lighting) exhibits

Peak Clipping - Or the reduction of the system peak loads, embodies one of the classic forms of load management. Peak clipping is generally considered as the reduction of peak load by using direct load control. Direct load control is most commonly practiced by direct utility control of either service to customer facilities or of customers' appliances. While many utilities consider this as means to reduce peaking capacity or capacity purchases and consider control only during the most probable days of system peak, direct load control can be used to reduce operating cost and dependence on critical fuels by economic dispatch.

Valley Filling - Is the second classic form of load management and applies to both gas and electric systems. Valley filling encompasses building off-peak loads. This may be particularly desirable where the long-run incremental cost is less than the average price of energy. Adding properly priced off-peak load under those circumstances decreases the average price. Valley filling can be accomplished in several ways, one of the most popular of which is new thermal energy storage (water heating and/or space heating) that displaces loads served by fossil fuels.

Load Shifting - Is the last classic form of load management and also applies to both gas and electric systems. This involves shifting load from on-peak to off-peak periods. Popular applications include use of storage water heating, storage space heating, coolness storage, and customer load shifts. The load shift from storage devices involves displacing what would have been conventional appliances.

Strategic Conservation - Is the load shape change that results from programs directed at end use consumption. Not normally considered load management, the change reflects a modification of the load shape involving a reduction in consumption as well as a change in the pattern of use. In employing energy conservation, the planner must consider what conservation actions would occur naturally and then evaluate the cost-effectiveness of possible intended programs to accelerate or stimulate those actions. Examples include weatherization and appliance efficiency improvement.

Strategic Load Growth - Is the load shape change that refers to a general increase in sales beyond the valley filling described previously. Load growth may involve increased market share of loads that are or can be, served by competing fuels, as well as economic development. Load growth may include electrification. Electrification is the term being employed to describe the new emerging electric technologies surrounding electric vehicles, industrial process heating, and automation. These have a potential for increasing the electric energy intensity of the industrial sector. This rise in intensity may be motivated by reduction in the use of fossil fuels and raw materials resulting in improved overall productivity.

Flexible Load Shape - Is a concept related to electric system reliability, a planning constraint. Once the anticipated load shape, including demand-side activities, is forecast over some horizon, the power supply planner studies the final optimum supply-side options. Among the many criteria he uses is reliability. Load shape can be flexible – if customers are presented with options as to the variations in quality of service that they are willing to allow in exchange for various incentives. The program involved can be variations of interruptible or curtailable load; concepts of pooled, integrated energy management systems; or individual customer load control devices offering service constraints.

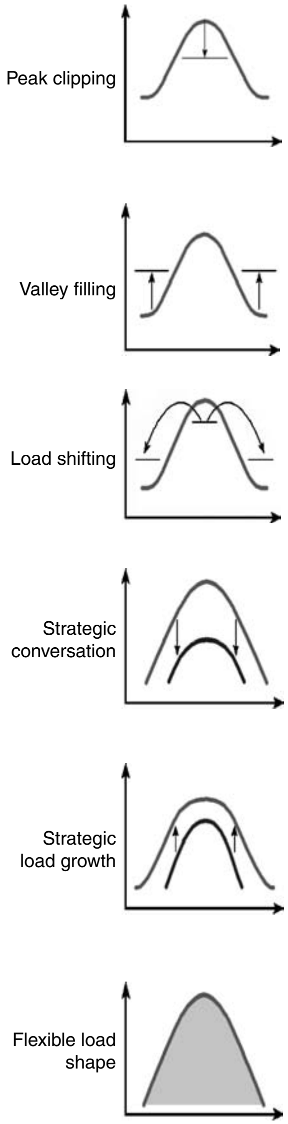

FIGURE 13.3 Six generic load shape objectives that can be considered during demand-side management planning.

typical and predictable demand or load patterns. The extent to which load pattern modification can be accommodated by a given end use is one factor used to select an end use for demand-side management. The second dimension of demand-side management alternatives involves choosing appropriate technology alternatives for each target end use. This process should consider the suitability of the technology for satisfying the load-shape objective. Even though a technology is suitable for a given end use, it may not produce the desired results. For example, although water-heater wraps are appropriate for reducing domestic water-heating energy consumption, they are not appropriate for load shifting. In this case, an option such as electric water-heating direct load control via receiver/switches would be a better choice. The third dimension involves investigating market implementation methods (see Section 13.4.5 for a description of potential implementation methods).

3. Evaluate and select program(s). The third step balances customer considerations, supplier considerations, and cost–benefit analyses to identify the most viable demand-side management alternative(s) to pursue. Although customers and suppliers act independently to alter the pattern of demand, the concept of demand-side management implies a supplier/customer relationship that produces mutually beneficial results. To achieve that mutual benefit, suppliers must carefully consider such factors as the manner in which the activity will affect the patterns and amount of demand (load shape), the methods available for obtaining customer participation, and the likely magnitudes of costs and benefits to both supplier and customer prior to attempting implementation.
4. Implement program(s). The fourth step, which takes place in several stages, is to implement the program(s). As a first step, a high level, demand-side management project team should be created with representation from the various departments and organizations, and with the overall control and responsibility for the implementation process. It is important for implementers to establish clear directives for the project team, including a written scope of responsibility, project team goals and time frame. When limited information is available on prior demand-side management program experiences, a pilot experiment may precede the program. Pilot experiments can be a useful interim step toward making a decision to undertake a major program. Pilot experiments may be limited either to a subregion or to a sample of consumers throughout an area. If the pilot experiment proves cost-effective, then the implementers may consider initiating the full-scale program.
5. Monitor program(s). The fifth step is to monitor the program(s). The ultimate goal of the monitoring process is to identify deviations from expected performance and to improve both existing and planned demand-side management programs. Monitoring and evaluation processes can also serve as a primary source of information on customer behavior and system impacts, foster advanced planning and organization within a demand-side management program, and provide management with the means of examining demand-side management programs as they develop.

13.4.2 Targeted End Use Sectors/Building Types

The three broad categories of end use sectors targeted for demand-side management programs are residential, commercial, and industrial. Each of these broad categories includes several subsectors. In some cases, the program will be designed for one or more broad sectors; in other cases, it may be designed for a specific subsector. For example, the residential sector can be divided into several subsectors including single family homes, multi-family homes, mobile homes, low income homes, etc. In addition, the commercial sector can be split into subsets, such as offices, restaurants, healthcare facilities, educational facilities, retail stores, grocery stores, hotels/motels, etc. There are also numerous specific industrial end users that may be potentially targeted for a demand-side management program. Moreover, the program designer may want to target a specific type or size of building within the chosen sector. The program could focus on new construction, old construction, renovations and retrofits, large customers, small customers, or a combination. Crosscutting programs target multiple end use sectors and/or multiple building types. Figure 13.4 illustrates the broad types of end use sectors and building types and how they relate to other aspects of demand-side management program planning.

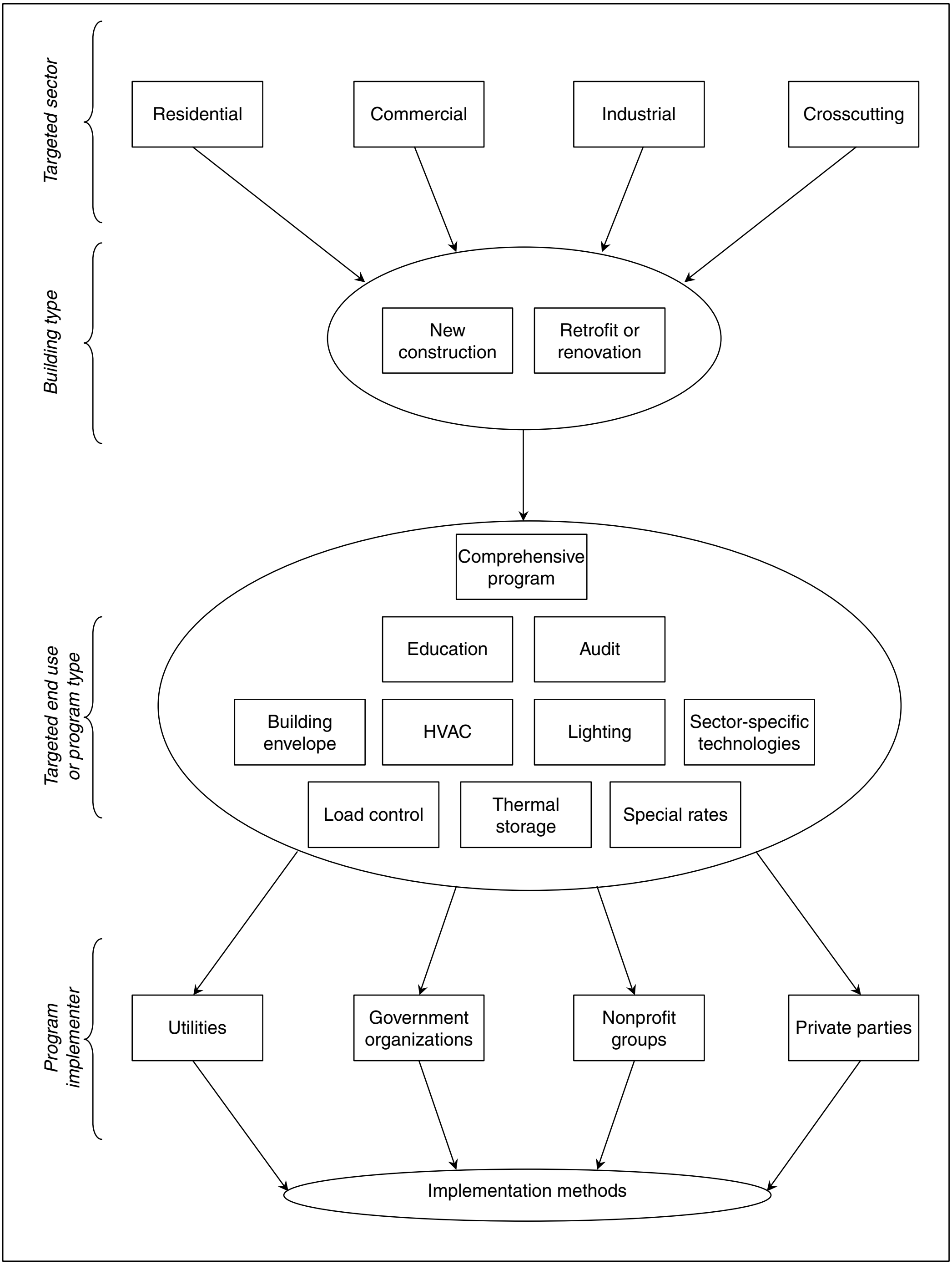

FIGURE 13.4 Relationship between end use sectors, building types, end use programs, and program implementers.

13.4.3 Targeted End Use Technologies/Program Types

There are several end use technologies or program types targeted in demand-side management programs. (See Figure 13.4 for representative end use technologies and program types.) Some programs are comprehensive, and crossover between end use technologies (e.g., see case study 1 below). Other technologies target-specific end use equipment such as lighting, air conditioners, dishwashers, etc. Still others target load control measures, such as those that shift loads to off-peak hours (e.g., thermal energy storage). Figure 13.4 shows representative end use technologies or program types and how they relate to other aspects of demand-side management program planning.

13.4.4 Program Implementers

Implementers of demand-side management programs are often utilities. However, other possible implementers include government organizations, nonprofit groups, private parties, or a collaboration of several entities (see Figure 13.4). Utilities and governments, in particular, have a special interest in influencing customers' demand—treating it not as fate but as choice—to provide better service at lower cost while increasing their own profits and reducing their business risks. Energy planners can choose from a wide range of market push and pull methods designed to influence consumer adoption and reduce barriers, as discussed in the next paragraph.

13.4.5 Implementation Methods

Among the most important dimension in the characterization of demand-side alternatives is the selection of the appropriate market implementation methods. Planners and policy makers can select from a variety of methods for influencing customer adoption and acceptance of demand-side management programs. The methods can be broadly classified into six categories. Table 13.1 lists examples for each category of market implementation method. The categories include:

1. Customer education. Many energy suppliers and governments have relied on some form of customer education to promote general customer awareness of programs. Brochures, bill inserts, information packets, clearinghouses, educational curricula, and direct mailings are widely used. Customer education is the most basic of the market implementation methods available and should be used in conjunction with one or more other market implementation method for maximum effectiveness.
2. Direct customer contact. Direct customer contact techniques refer to face-to-face communication between the customer and an energy supplier or government representative to encourage greater customer acceptance of programs. Energy suppliers have for some time employed marketing and customer service representatives to provide advice on appliance choice and operation, sizing of heating/cooling systems, lighting design, and even home economics. Direct customer contact can be accomplished through energy audits, specific program services (e.g., equipment servicing), store fronts where information and devices are displayed, workshops, exhibits, onsite inspection, etc. A major advantage of these methods is that they allow the implementer to obtain feedback from the consumer, thus providing an opportunity to identify and respond to major customer concerns. They also enable more personalized marketing, and can be useful in communicating interest in and concern for controlling energy costs.
3. Trade ally cooperation. Trade ally cooperation and support can contribute significantly to the success of many demand-side management programs. A trade ally is defined as any organization that can influence the transactions between the supplier and its customers or between implementers and consumers. Key trade ally groups include home builders and contractors, local chapters of professional societies, technology/product trade groups, trade associations, and associations representing wholesalers and retailers of appliances and energy consuming devices. Depending on the type of trade ally organization, a wide range of services are performed, including

TABLE 13.1 Examples of Market Implementation Methods

Market Implementation Method	Illustrative Objective	Examples
Customer education	Increase perceived value of energy services Increase customer awareness of programs	Bill inserts Brochures Information packets Displays Clearinghouses Direct mailings
Direct customer contact	Through face-to-face communication, encourage greater customer acceptance, and response to programs	Energy audits Direct installation Store fronts Workshops/energy clinics Exhibits/displays Inspection services
Trade ally cooperation (i.e., architects, engineers, appliance dealers, heating/cooling contractors)	Increase capability in marketing and implementing programs Obtain support and technical advice on customer adoption of demand-side technologies	Cooperative advertising and marketing Training Certification Selected product sales/service
Advertising and promotion	Increase public awareness of new programs Influence customer response	Mass media (radio, TV, and newspaper) Point-of-purchase advertising
Alternative pricing	Provide customers with pricing signals that reflect real economic costs and encourage the desired market response	Demand rates Time-of-use rates Off-peak rates Seasonal rates Inverted rates Variable levels of service Promotional rates Conservation rates
Direct incentives	Reduce up-front purchase price and risk of demand-side technologies to the customer Increase short-term market penetration Provide incentives to employees to promote demand-side management programs	Low- or no-interest loan Cash grants Subsidized installation/modification Rebates Buyback programs Rewards to employees for successful marketing of demand-side management programs

development of standards and procedures, technology transfer, training, certification, marketing/sales, installation, maintenance, and repair. Generally, if trade ally groups believe that demand-side management programs will help them (or at least not hinder their business), they will likely support the program.

4. Advertising and promotion. Energy suppliers and government energy entities have used a variety of advertising and promotional techniques. Advertising uses various media to communicate a message to customers in order to inform or persuade them. Advertising media applicable to demand-side management programs include radio, television, magazines, newspapers, outdoor advertising, and point-of-purchase advertising. Promotion usually includes activities to support advertising, such as press releases, personal selling, displays, demonstrations, coupons, and contest/awards. Some prefer the use of newspapers based on consumer research that found this

medium to be the major source of customer awareness of demand-side management programs. Others have found television advertising to be more effective.

5. Alternative pricing. Pricing as a market-influencing factor generally performs three functions: (1) transfers to producers and consumers information regarding the cost or value of products and services being provided, (2) provides incentives to use the most efficient production and consumption methods, and (3) determines who can afford how much of a product. These three functions are closely interrelated. Alternative pricing, through innovative schemes can be an important implementation technique for utilities promoting demand-side options. For example, rate incentives for encouraging specific patterns of utilization of electricity can often be combined with other strategies (e.g., direct incentives) to achieve electric utility demand-side management goals. Pricing structures include time-of-use rates, inverted rates, seasonal rates, variable service levels, promotional rates, off-peak rates, etc., A major advantage of alternative pricing programs over some other types of implementation techniques is that the supplier has little or no cash outlay. The customer receives a financial incentive, but over a period of years, so that the implementer can provide the incentives as it receives the benefits.
6. Direct incentives. Direct incentives are used to increase short-term market penetration of a cost control/customer option by reducing the net cash outlay required for equipment purchase or by reducing the payback period (i.e., increasing the rate of return) to make the investment more attractive. Incentives also reduce customer resistance to options without proven performance histories or options that involve extensive modifications to the building or the customer's lifestyle. Direct incentives include cash grants, rebates, buyback programs, billing credits, and low-interest or no-interest loans. One additional type of direct incentive is the offer of free, or very heavily, subsidized, equipment installation or maintenance in exchange for participation. Such arrangements may cost the supplier more than the direct benefits from the energy or demand impact, but can expedite customer recruitment and allow the collection of valuable empirical performance data.

Energy suppliers, utilities, and government entities have successfully used many of these marketing strategies. Typically, multiple marketing methods are used to promote demand-side management programs. The selection of the individual market implementation method or mix of methods depends on a number of factors, including:

- Prior experience with similar programs
- Existing market penetration
- The receptivity of policy makers and regulatory authorities
- The estimated program benefits and costs to suppliers and customers
- Stage of buyer readiness
- Barriers to implementation

Some of the most innovative demand-side marketing programs started as pilot programs to gauge consumer acceptance and evaluate program design prior to large-scale implementation.

The objective of the market implementation methods is to influence the marketplace and to change customer behavior. The key question for planners and policy makers is the selection of the market implementation method(s) to obtain the desired customer acceptance and response. Customer acceptance refers to customer willingness to participate in a market implementation program, customer decisions to adopt the desired fuel/appliance choice and efficiency, and behavior change as encouraged by the supplier, or state. Customer response is the actual load shape change that results from customer action, combined with the characteristics of the devices and systems being used.

Customer acceptance and responses are influenced by the demographic characteristics of the customer, income, knowledge, and awareness of the technologies and programs available, and decision criteria such as cash flow and perceived benefits and costs, as well as attitudes and motivations. Customer acceptance and response are also influenced by other external factors, such as economic conditions, energy prices, technology characteristics, regulation, and tax credits.

13.4.6 Representative Programs in the U.S.

Numerous demand-side management programs are implemented in the U.S. yearly by various organizations. In recent years, the California Best Practices Project Advisory Committee and their contractor, Quantum Consulting, Inc., have reviewed and compared many demand-side management programs that focus on energy conservation and efficiency as part of a National Energy Efficiency Best Practices Study. The results of the study are included in a series of reports. Table 13.2 provides an overview of more than 60 programs evaluated in the National Energy Efficiency Best Practices Study that were implemented between 1999 and 2004. The type of program, program name, implementer(s), achieved energy and demand savings, program cost, and review period are listed for each program. Where values were not available, the abbreviation "NA" is used. The table shows the wide variety of programs offered spanning the residential and nonresidential sectors. Some programs provide general information and training, others target specific end uses such as lighting, heating, ventilation and air conditioning (HVAC), and new construction, and still others are comprehensive in nature. Yearly costs for the programs in Table 13.2 ranged from \$150,000 for a nonresidential HVAC program offered to customers in a single service territory to \$25.9 million for a statewide comprehensive program. Reported energy savings ranged from 400 MWh for a residential audit and information program offered in a single service territory to 271,560 MWh for a northwest regional ENERGY STAR® residential lighting program. The following section examines four of the programs from Table 13.2 in more detail.

13.5 Case Studies

13.5.1 Case Study 1: 2001 California 20/20 Rebate Program[1]

In response to a crisis of constrained supply, skyrocketing electricity prices, and fear of summer blackouts, California launched an enormous effort in 2001 to conserve energy and reduce electricity demand. This effort was primarily embodied in emergency legislation that provided additional funding and led to the rapid development and deployment of hundreds of energy efficiency programs administered and implemented by a variety of entities. One of the most successful programs was the 2001 California 20/20 Rebate Program (see Table 13.3 for program summary). This program provided rebates to residential and small commercial/industrial customers of the state's investor-owned utilities for reducing monthly electricity usage from June through September, 2001. Customers were offered a 20% rebate off of the electricity commodity portion of their energy bill for lowering their total monthly electricity use by at least 20% compared to the same month of the previous year. In addition, large commercial/industrial customers with time-of-use meters received a 20% rebate off of their summer on-peak demand and energy charges for reducing on-peak electricity use by at least 20%. The program was executed with cooperation and funding by several state agencies and organizations. Because the program overlapped with other California programs such as the "Flex Your Power" marketing campaign, it was difficult to accurately credit energy savings specifically to the 20/20 Rebate Program. In a study for the California Measurement Advisory Council (CALMAC), which involved evaluating the success of California's 2001 programs, Global Energy Partners (Global) attempted to adjust reported savings from the 20/20 Rebate Program to discount the effect of double counting. The reported accomplishments of the program were 5.3 million MWh in energy savings and 2616 MW in demand savings. With Global's adjustments for double counting among programs, the energy savings were estimated to be 3.1 MWh.

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[1] Data from Global Energy Partners, 2003. *California Summary Study of 2001 Energy Efficiency Programs*. Publication 02-1099. Global Energy Partners, LLC, Lafayette, CA.

TABLE 13.2 Examples of Recent Demand-Side Management Programs in the U.S.

Program Type	Program Name	Implementer(s)	Time Period	Cost	Energy Savings	Demand Savings
Residential lighting[a]	2002 California Crosscutting Statewide Residential Lighting Program	Pacific Gas & Electric Co. (PG&E); Southern California Edison (SCE); San Diego Gas & Electric Co. (SDG&E)	2002	$9.4 million	162,888 MWh	21,365 kW
	2002 Efficient Products Program—Lighting Component	Efficiency Vermont (EVT)	2002	$1.6 million	11,039 MWh	1740 kW winter 1074 kW summer
	2002 Massachusetts Electric—Residential Lighting Program	Massachusetts Electric	2002	$3.3 million	18,037 MWh	5084 kW
	2002 Midwest Change a Light, Change the World Campaign	Midwest Energy Efficiency Alliance (MEEA)	Fall 2002	$630,000	10,198 MWh	NA
	2001 ENERGY STAR® Residential Lighting Program	Northwest Energy Efficiency Alliance (NW Alliance)	2001	$2.6 million	271,560 MWh	NA
	2000–2001 Retail Lighting Program	United Illuminating	2000–2001	$3.0 million	7808 MWh	NA
Residential AC[b]	2002 Keep Cool Air Conditioner Bounty Program	New York State Energy Research and Development Authority (NYSERDA)	2002	NA	27,208 MWh	44,813 kW
	2002 California Statewide Single-Family Rebate Program AC Component	PG&E; SCE; SDG&E	2002	NA (included in overall Single-Family Rebate Program budget)	8399 MWh	NA
	2002 New Jersey Clean Energy™ Collaborative Residential AC Component	Conectiv Power Delivery; Jersey Central Power & Light Co. (JCP&L); Public Service Electric & Gas Co. (PSE&G); Rockland Electric Company (RECO)	2002	$24.2 million	NA	NA
	2003 Air Conditioning Distributor Market Transformation Program	Oncor	2003	$5.9 million	13,478 MWh	10,800 kW

	2002 Residential Air Conditioning Program	Florida Power and Light (FPL)	2002	$18.0 million	78,957 MWh	37,360 kW
Single-Family Comprehensive[c]	2001–2002 Central Valley Hard-to-Reach Mobile Home Energy Savings Program	American Synergy Corp.	Oct. 2002–Oct. 2003	$1.4 million	3,447 MWh	1,329 kW
	2002 California Statewide Single-Family Energy Efficiency Rebate Program	PG&E; SCE; SDG&E	2002	$25.9 million	36,028 MWh	31,869 kW
	1999–2000 Residential High-Use Program	NSTAR	Aug. 1999–Aug. 2000	$3.5 million	3,179 MWh	1,164 kW winter 831 kW summer
	2001 Energy Wise Program	National Grid U.S.A.	2001	$1.2 million	3,461 MWh	743 kW
	2002 Efficiency Equipment Load Program	Sacramento Municipal Utility District (SMUD)	2002	$2.4 million	1,254 MWh	700 kW
	2002 Residential Weatherization Program	Tacoma Power	2002	$938,000	2,031 MWh	NA
Multi-Family Comprehensive[d]	2002 Multi-Family Incentive Program	Austin Energy	2002	$581,300	3,121 MWh	2,080 kW
	2002 California Statewide Multi-Family Program	PG&E; SCE; SDG&E	2002	$8.3 million	9,050 MWh gross 7,621 MWh net	1,853 kW
	2003 Home Energy Savings Program—Multi-Family Component	The City of Portland/Energy Trust of Oregon, Inc.	Jan.–Dec. 2003	$1.0 million	7,000 MWh gross 2,578 MWh net	NA
	2002–2003 Apartment & Condo Efficiency Services	Focus on Energy™/Wisconsin Energy Conservation Corp. (WECC)	Sep. 2002–Aug. 2003	$5.1 million	12,963 MWh net	2,391 kW net
	2002 Energy Wise—Multi-Family Component	National Grid	2002	$2.3 million	3,487 MWh gross 2,706 MWh net	400 kW winter 600 kW summer
	2000 Multi-Family Conservation Program	Seattle City Light (SCL)	2000	$1.2 million	2,769 MWh	NA
Audits & Information[e]	2002 Home Performance with ENERGY STAR Program	NYSERDA	2002	$4.0 million	741 MWh	80 kW
	2000 Time-of-Sale Home Inspection Program	SCE; GeoPraxis, Inc.	2000	$282,000	1,974 MWh	NA

(continued)

TABLE 13.2 (*Continued*)

Program Type	Program Name	Implementer(s)	Time Period	Cost	Energy Savings	Demand Savings
	2002 Residential Conservation Services Audit Program	National Grid	2002	\$2.8 million	2,677 MWh	406 kW
	2002 E+ Energy Audit for Your Home Program	Northwestern Energy	2002	\$1.3 million	4,713 MWh	884 kW
	2002 Residential Energy Advisory Services Program	SMUD	2002	\$1.1 million	400 MWh	70 kW
	2002 California Statewide Home Energy Efficiency Program	PG&E; SCE; SDG&E	2002	\$2.0 million	8,700 MWh	4,190 kW
Residential New Construction[f]	2001–2002 Austin Green Building Program	Austin Energy	FY 2000–2001	\$605,000	7,666 MWh	3,630 kW
	2002 California Energy Star New Homes Program	PG&E; SCE; SDG&E	2002	\$15.2 million	10,655 MWh	22,262 kW
	2002 New Jersey ENERGY STAR Homes	Clean Energy for New Jersey	2002	\$10.9 million	3,262 MWh	3,415 kW
	2002 Texas ENERGY STAR Homes Program	Oncor	2002	\$5.2 million	24,700 MWh	7,410 kW
	2002 Tucson Guarantee Home Program	Tucson Electric Power	2002	\$3.0 million	3,023 MWh	4,094 kW
	2001 Vermont ENERGY STAR Homes	EVT	2001	\$920,000	841 MWh	278 kW
	2001–2002 Wisconsin ENERGY STAR Program	WECC	2002–2003	\$2.9 million	1,049 MWh	247 kW
Nonresidential Lighting[g]	2003 Lighting Efficiency Program	Xcel Energy	2003	\$2.3 million for all commercial & industrial \$1.1 million for businesses <500kW	41,780 MWh for all commercial & industrial 19,433 MWh for businesses <500kW	7896 kW for all commercial & industrial 3928 kW for businesses <500kW
	2002–2003 Business Energy Services Team Program	KEMA-XENERGY	2002–2003	\$941,000	2,704 MWh	559 kW
	2002 EZ Turnkey Program	SDG&E	2002	\$1.3 million	3,121 MWh	570 kW
	2003 Small Commercial Prescriptive Lighting Initiative	SMUD	2003	\$2.7 million	19,865 MWh	3,920 kW

	2002 Small Business Energy Advantage Program	Connecticut Light & Power (CL&P)	2003	$4.6 million	16,167 MWh	3,570 kW
	2002 California Statewide Express Efficiency Program	PG&E; SCE; SDG&E	2002	$21.7 million	244,346 MWh	43,000 kW
Nonresidential HVAC[h]	New England Efficiency Partnership (NEEP) Cool Choice Program	CL&P; United Illuminating; Cape Light Compact; Massachusetts Electric Co.; Nantucket Electric Co.; NSTAR Electric; Western Massachusetts Electric Co.; Conectiv Power Delivery; JCP&L; PSE&G; Narragansett Electric Co.; Burlington Electric; EVT	2002	$2.3 million	3929 MWh	3518 kW
	Avista Rooftop HVAC Maintenance Program	Avista Utilities	2001	$1.8 million	13,000 MWh	NA
	California Express Efficiency HVAC Component	PG&E; SCE; SDG&E	2002	NA (included in overall Express Efficiency program budget)	2,901 MWh	NA
	Los Angeles Department of Water and Power (DWP) Chiller Efficiency	Los Angeles DWP	2003–2004	$786,430	7,174 MWh	5,666 kW
	FP&L Commercial/Industrial HVAC Program	FPL	2002	$5.4 million	NA	NA
	Glendale Water and Power Check Me!	Glendale Water and Power	2001	$150,000	25,128 MWh	358 kW
Nonresidential Large Comprehensive Incentive[i]	Non-Residential Standard Performance Contract	PG&E; SCE; SDG&E	2002	$23.0 million	167,300 MWh	28,441 kW
	Energy $mart™ C/I Performance	NYSERDA	2001–2002	$34.2 million	204,500 MWh	53,886 kW
	Energy Opportunities	United Illuminating	2002	$1.3 million	10,772 MWh	2,627 kW
	Power Smart	BC Hydro	2004	$7.8 million industrial $17.6 million commercial and government	54,000 MWh industrial 74,000 MWh commercial and government	NA

(continued)

TABLE 13.2 (***Continued***)

Program Type	Program Name	Implementer(s)	Time Period	Cost	Energy Savings	Demand Savings
	Custom Efficiency	Xcel Energy (Colorado)	2002–2005	$12.2 million	76,167 MWh	40,077 kW
	Custom Services	CL&P	2003	$8.6 million	24,853 MWh	NA
	Energy Initiative	National Grid	2002	$9.7 million	30,862 MWh	6,089 kW
	Energy Shared Savings	WP&L (Alliant) Wisconsin	2001	$21.9 million	104,325 MWh	16,000 kW
	Business Energy Services	EVT	2002	$1.1 million	4,955 MWh	NA
	Commercial & Industrial Custom Retrofit	SMUD	2002	$7.3 million	NA	NA
New Construction Information & Services[j]	Energy Conscious Construction	Northeast Utilities	2002	$7.4 million	33,365 MWh	NA
	Energy Design Assistance	Xcel Energy	2002	$3.4 million	63,093 MWh	19,100 kW
	Design 2000 Plus	National Grid	2002	$13.9 million	31,804 MWh	6,429 kW
	Savings by Design	PG&E; SCE; SDG&E	2002	$22.6 million	82,697 MWh	18,600 kW
	Construction Solutions	NSTAR	2001	$7.9 million	14,230 MWh	1,710 kW
	Commercial & Industrial New Construction Program	Hawaiian Electric Co. (HECO)	1999	$935,000	5584 MWh	821 kW

[a] Quantum Consulting, Inc., 2004. *Residential Lighting Best Practices Report*, *Vol. 1*, *National Energy Efficiency Best Practices Study*. Quantum Consulting, Inc., Berkeley, CA.

[b] Quantum Consulting, Inc., 2004. *Residential Air Conditioning Best Practices Report*, *Vol. R2*, *National Energy Efficiency Best Practices Study*. Quantum Consulting Inc., Berkeley, CA.

[c] Quantum Consulting, Inc., 2004. *Residential Single-Family Comprehensive Weatherization Best Practices Report*, *Vol. R4*, *National Energy Efficiency Best Practices Study*. Quantum Consulting Inc., Berkeley, CA.

[d] Quantum Consulting, Inc., 2004. *Residential Multi-Family Comprehensive Best Practices Report*, *Vol. R5*, *National Energy Efficiency Best Practices Study*. Quantum Consulting Inc., Berkeley, CA.

[e] Quantum Consulting, Inc., 2004. *Residential Audit Programs Best Practices Report*, *Vol. R7*, *National Energy Efficiency Best Practices Study*. Quantum Consulting Inc., Berkeley, CA.

[f] Quantum Consulting, Inc., 2004. *Residential New Construction Best Practices Report*, *Vol. R8*, *National Energy Efficiency Best Practices Study*. Quantum Consulting Inc., Berkeley, CA.

[g] Quantum Consulting, Inc., 2004. *Non-Residential Lighting Best Practices Report*, *Vol. NR1*, *National Energy Efficiency Best Practices Study*. Quantum Consulting Inc., Berkeley, CA.

[h] Quantum Consulting, Inc., 2004. *Non-Residential HVAC Best Practices Report*, *Vol. NR2*, *National Energy Efficiency Best Practices Study*. Quantum Consulting Inc., Berkeley, CA.

[i] Quantum Consulting, Inc., 2004. *Non-Residential Large Comprehensive Incentive Programs Best Practices Report*, *Vol. NR5*, *National Energy Efficiency Best Practices Study*. Quantum Consulting Inc., Berkeley, CA.

[j] Quantum Consulting, Inc., 2004. *Non-Residential New Construction Best Practices Report*, *Vol. NR8*, *National Energy Efficiency Best Practices Study*. Quantum Consulting Inc., Berkeley, CA.

TABLE 13.3 Case Study 1: 2001 California 20/20 Rebate Program

Description

The 20/20 Rebate program was a statewide program designed to address California's energy crisis in 2001. It provided rebates to residential and small commercial/industrial customers of the state's investor-owned utilities for reducing monthly electricity usage from June through September, 2001. Customers were offered a 20% rebate off of the electricity commodity portion of their energy bill for lowering their total monthly electricity use by at least 20% compared to the same month of the previous year. In addition, large commercial/industrial customers with time-of-use meters received a 20% rebate off of their summer on-peak demand and energy charges for reducing on-peak electricity use by at least 20%

Targeted Sector/Building Type

All residential, commercial, and industrial customers of California's investor-owned utilities

Targeted End Use Technology/Program Type

Rebate for reducing electricity use by 20% relative to same month in previous year

Program Implementer

Executive order of Governor Gray Davis; included cooperation and funding by several state agencies and organizations

Budget for Year

$350 million for 2001

Program Results

Reported energy savings = 5,258,000 MWh[a]
Adjusted energy savings = 3,053,000 MWh[b]
Demand savings = 2616 MW[c]

[a] Goldman and Barbose. 2002. *California Customer Load Reductions During the Electricity Crisis: Did they Help to Keep the Lights On?* Lawrence Berkeley National Laboratories, Berkeley, CA.

[b] During an evaluation of California's 2001 energy efficiency programs for the California Measurement Advisory Council (CALMAC), Global Energy Partners adjusted the 20/20 Rebate program's energy savings to correct for double counting. *Data Source*: Global Energy Partners. 2003. *California Summary Study of 2001 Energy Efficiency Programs*. Publication 02-1099. Global Energy Partners, LLC, Lafayette, CA.

[c] This value represents "residual" peak demand reduction for September 2001 attributable to the combined effects of the 20/20 Rebate program, the *Flex Your Power* public awareness campaign, electricity rates, and voluntary demand-side management. *Data Source*: California Energy Commission. 2001. *California Market Report*. Sacramento, CA, October.

The program budget for 2001 was $350 million. Although this program was hugely successful during the crisis of 2001, it is difficult to sustain a program of this type in the absence of an immediate energy crisis. As a result, it was discontinued after 2002.

13.5.2 Case Study 2: 2002 California Statewide Residential Lighting Program[2]

The 2002 California Statewide Residential Lighting Program was designed in response to the 2001 energy crisis experienced in California (see Table 13.4 for program summary). Its purpose was to encourage greater penetration of energy efficient lamps and fixtures into the residential sector. The products covered included compact fluorescent lamps, torchieres, ceiling fans, and complete fixtures. This was accomplished by providing rebates to manufacturers (manufacturer upstream buydown) to lower wholesale costs as well as by providing instant rebates to consumers at the point of sale. The program was implemented by three large investor-owned utilities in the state: Pacific Gas & Electric (PG&E), Southern California Edison (SCE), and San Diego Gas & Electric (SDG&E). Each utility had in-house management responsibilities. The program leveraged on relationships with manufacturers and retailers established in previous lighting programs. Progress was tracked by using data on the number of products delivered by manufacturers and retailer sales information. In all, 5,502,518 lamps, 24,932 fixtures, 6736 torchieres, and 50 ceiling fans with bulbs were rebated during 2002. The estimated program accomplishments

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[2] Data from Quantum Consulting, Inc., 2004. *Residential Lighting Best Practices Report, Vol. 1, National Energy Efficiency Best Practices Study.* Quantum Consulting, Inc., Berkeley, CA.

TABLE 13.4 Case Study 2: 2002 California Statewide Residential Lighting Program

Description

The 2002 California Residential Lighting program was designed to build upon the success of earlier lighting efficiency programs, while at the same time address the more immediate energy needs brought about by the 2001 energy crisis in California. The program was unique in that it was implemented identically across the State's investor-owned utility service territories. It offered point-of-sale rebates and manufacturer buy-down to reduce lighting costs to residential customers

Targeted Sector/Building type

All residential

Targeted End Use Technology/Program Type

Multiple lighting measures

Program Implementer

California investor-owned utilities; PG&E, SCE, and SDG&E

Budget for Year

$9.4 million for 2002; $7.3 million total incentives paid

Program Results

Reported energy savings = 162,888 MWh
Demand savings = 21.4 MW

Source: From Quantum Consulting, Inc., *Residential Lighting Best Practices Report*, *Vol. 1*, *National Energy Efficiency Best Practices Study*. Quantum Consulting Inc., Berkeley, CA, 2004.

were 162,888 MWh in energy savings, and 21.4 MW in demand savings. The total program cost was $9.4 million.

13.5.3 Case Study 3: 2003 Xcel Energy Lighting Efficiency Program[3]

The Xcel Energy Lighting Efficiency Program was designed to encourage energy efficient lighting design for commercial and industrial customers in Minnesota (see Table 13.5 for program summary). The implementer was Xcel Energy, a utility company. The program targeted all commercial and industrial customers, as well as small (less than 500 kW) businesses. It offered prescriptive and custom rebates, energy assessments, and low-interest financing for projects. The rebates were applicable both to lighting in new construction and to replacement of lighting in existing buildings. The customers or vendors were responsible for installing the lighting equipment. Xcel Energy managed the program with in-house personnel. The program managers were responsible for approving projects, monitoring applications, and verifying and tracking installations. During 2003, almost 900 prescriptive lighting projects were undertaken. The estimated program accomplishments were energy savings of 41,780 MWh for all commercial and industrial customers and 19,433 MWh for small businesses. The estimated demand savings were 7.9 and 3.9 MW, respectively, for commercial and industrial customers and for small businesses. The program costs for the year were $2.3 million for commercial and industrial customers, and $1.1 million for small businesses.

13.5.4 Case Study 4: 2002 Northeast Energy Efficiency Partnership Cool Choice Program[4]

The 2002 Northeast Energy Efficiency Partnership (NEEP) Cool Choice program was designed to increase penetration of high efficiency cooling systems in commercial and industrial buildings in the

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[3] Data from Quantum Consulting, Inc. 2004. *Non-Residential Lighting Best Practices Report*, *Vol. NR1*, *National Energy Efficiency Best Practices Study*. Quantum Consulting Inc., Berkeley, CA.

[4] Data from Quantum Consulting, Inc. 2004. *Non-Residential HVAC Best Practices Report*, *Vol. NR2*, *National Energy Efficiency Best Practices Study*. Quantum Consulting Inc., Berkeley, CA.

TABLE 13.5 Case Study 3: 2003 Xcel Energy Lighting Efficiency Program

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Description
The 2003 Xcel lighting efficiency program offered low-cost energy assessments, low-interest financing, and rebates for replacing lighting in existing buildings and for adding energy efficient lighting during new construction. The rebates were both prescriptive and custom in nature

Targeted Sector/Building Type
All commercial and industrial customers
Small business customers $<$ 500 kW

Targeted End Use Technology/Program Type
Multiple lighting measures

Program Implementer
Xcel energy of minnesota

Budget for Year
All commercial and industrial customers: $2.29 million for 2003; $1.51 million total incentives paid
Small business customers $<$ 500 kW: $1.09 million for 2003; $0.66 million total incentives paid

Program Results
Reported energy savings = 41,780 MWh (net) for all commercial and industrial customers
= 19,433 MWh for small business customers $<$ 500 kW
Demand savings = 7.9 MW (summer) for all commercial and industrial customers
= 3.9 MW for small business customers $<$ 500 kW
Almost 900 prescriptive rebates were offered during 2003

Source: From Quantum Consulting, Inc., *Non-Residential Lighting Best Practices Report*, *Vol. NR1*, *National Energy Efficiency Best Practices Study*. Quantum Consulting, Inc., Berkeley, CA, 2004.

Northeast states of Connecticut, Rhode Island, Vermont, Massachusetts, and New Jersey (see Table 13.6 for program summary). NEEP, which is a collaboration of over a dozen utilities in the Northeast region, administered the program. The 2002 program was a continuation of an on-going program established in 1998 to educate HVAC contractors in the correct installation of HVAC systems and to encourage them to

TABLE 13.6 Case Study 4: 2002 Northeast Energy Efficiency Partnership (NEEP) Cool Choice Program

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Description
The 2002 Cool Choice program was an incentive-based program that provided rebates to commercial and industrial customers who purchased high efficiency air conditioning systems. The rebates were intended to offset the higher costs associated with energy efficient units

Targeted Sector/Building Type
All commercial and industrial customers

Targeted End Use Technology/Program Type:
High efficiency direct expansion air conditioners and heat pumps; economizers

Program Implementer
NEEP

Budget for Year
$2.3 million for 2002

Program Results
Reported energy savings = 3929 MWh
Demand savings = 3.5 MW

Source: From Quantum Consulting, Inc., *Non-Residential HVAC Best Practices Report*, *Vol. NR2*, *National Energy Efficiency Best Practices Study*, Quantum Consulting Inc., Berkeley, CA, 2004.

up-sell high efficiency units to consumers. The program offers an incentive to customers to help offset the greater costs associated with high-efficiency air-conditioning equipment. The incentive is based on the incremental improvement in efficiency provided by the energy efficient alternative, and covered 80% of the incremental costs for air conditioning systems of 30 tn. or less. An outside implementer managed the program and outreached to HVAC contractors, who then outreached to customers. The estimated program accomplishments for 2002 were 3929 MWh in energy savings and 3.5 MW in demand savings. The total program cost for the year was $2.3 million.

13.6 Conclusions

Since the early 1970s, economic, political, social, technological, and resource supply factors have combined to change the energy industry's operating environment and its outlook for the future. Many are faced with staggering capital requirements for new plants, significant fluctuations in demand and energy growth rates, declining financial performance and political or regulatory and consumer concern about rising prices. Although demand-side management is not a cure-all for these difficulties, it does provide for great many additional alternatives. These demand-side alternatives are equally appropriate for consideration by utilities, energy suppliers, energy-service suppliers, and government entities. Implementation of demand-side measures not only benefits the implementing organization by influencing load characteristics, delaying the need for new energy resources, and in general improving resource value, but it also provides benefits to customers such as reduced energy bills and/or improved performance from new technological options. In addition, society as a whole receives economic, environmental, and national security benefits. For example, because demand-side management programs can postpone the need for new power plants, the costs and emissions associated with fossil-fueled electricity generation are avoided. Demand-side management programs also tend generate more jobs and expenditures within the regions where the programs are implemented, boosting local economies. Moreover, demand-side management programs can help reduce a country's dependence on foreign oil imports, improving national security. Demand-side management alternatives, particularly those focused on energy conservation and efficiency, will continue to hold an important role in resources planning in the US and abroad, and will be a critical element in the pursuit of a sustainable energy future.

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A1

The International System of Units, Fundamental Constants, and Conversion Factors

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The International system of units (SI) is based on seven base units. Other derived units can be related to these base units through governing equations. The base units with the recommended symbols are listed in Table A1.1. Derived units of interest in solar engineering are given in Table A1.2.

Standard prefixes can be used in the SI system to designate multiples of the basic units and thereby conserve space. The standard prefixes are listed in Table A1.3.

Table A1.4 lists some physical constants that are frequently used in solar engineering, together with their values in the SI system of units.

Conversion factors between the SI and English systems for commonly used quantities are given in Table A1.5.

TABLE A1.1 The Seven SI Base Units

Quantity	Name of Unit	Symbol
Length	Meter	m
Mass	Kilogram	kg
Time	Second	s
Electric current	Ampere	A
Thermodynamic temperature	Kelvin	K
Luminous intensity	Candela	cd
Amount of a substance	Mole	mol

TABLE A1.2 SI Derived Units

Quantity	Name of Unit	Symbol
Acceleration	Meters per second squared	m/s^2
Area	Square meters	m^2
Density	Kilogram per cubic meter	kg/m^3
Dynamic viscosity	Newton-second per square meter	$N\ s/m^2$
Force	Newton (=1 kg m/s^2)	N
Frequency	Hertz	Hz
Kinematic viscosity	Square meter per second	m^2/s
Plane angle	Radian	rad
Potential difference	Volt	V
Power	Watt(=1 J/s)	W
Pressure	Pascal (=1 N/m^2)	Pa
Radiant intensity	Watts per steradian	W/sr
Solid angle	Steradian	sr
Specific heat	Joules per kilogram–Kelvin	J/kg K
Thermal conductivity	Watts per meter–Kelvin	W/m K
Velocity	Meters per second	m/s
Volume	Cubic meter	m^3
Work, energy, heat	Joule (=1 N/m)	J

TABLE A1.3 English Prefixes

Multiplier	Symbol	Prefix	Multiplier	Multiplier Symbol
10^{12}	T	Tera	10^3	M (thousand)
10^9	G	Giga	10^6	MM (million)
10^6	m	Mega		
10^3	k	Kilo		
10^2	h	Hecto		
10^1	da	Deka		
10^{-1}	d	Deci		
10^{-2}	c	Centi		
10^{-3}	m	Milli		
10^{-6}	μ	Micro		
10^{-9}	n	Nano		
10^{-12}	p	Pico		
10^{-15}	f	Femto		
10^{-18}	a	Atto		

TABLE A1.4 Physical Constants in SI Units

Quantity	Symbol	Value
Avogadro constant	N	6.022169×10^{26} kmol^{-1}
Boltzmann constant	k	1.380622×10^{-23} J/K
First radiation constant	$C_1 = 2\pi h C^2$	3.741844×10^{-16} W m^2
Gas constant	R	8.31434×10^3 J/kmol K
Planck constant	h	6.626196×10^{-34} J s
Second radiation constant	$C_2 = hc/k$	1.438833×10^{-2} m K
Speed of light in a vacuum	C	2.997925×10^8 m/s
Stefan–Boltzmann constant	σ	5.66961×10^{-8} W/m^2 K^4

TABLE A1.5 Conversion Factors

Physical Quantity	Symbol	Conversion Factor
Area	A	1 ft.^{2} = 0.0929 m^2
		1 acre = 43,560 ft.^{2} = 4047 m^2
		1 hectare = 10,000 m^2
		1 square mile = 640 acres
Density	ρ	1 lb$_m$/ft.^{3} = 16.018 kg/m^3
Heat, energy, or work	Q or W	1 Btu = 1055.1 J
		1 kWh = 3.6 MJ
		1 Therm = 105.506 MJ
		1 cal = 4.186 J
		1 ft. lb$_f$ = 1.3558 J
Force	F	1 lb$_f$ = 4.448 N
Heat flow rate, refrigeration	q	1 Btu/h = 0.2931 W
		1 ton (refrigeration) = 3.517 kW
		1 Btu/s = 1055.1 W
Heat flux	q/A	1 Btu/h ft.^{2} = 3.1525 W/m^2
Heat-transfer coefficient	h	1 Btu/h ft.^{2} F = 5.678 W/m^2 K
Length	L	1 ft. = 0.3048 m
		1 in. = 2.54 cm
		1 mi = 1.6093 km
Mass	m	1 lb$_m$ = 0.4536 kg
		1 ton = 2240 lbm
		1 tonne (metric) = 1000 kg
Mass flow rate	$\dot{m}$	1 lb$_m$/h = 0.000126 kg/s
Power	$\dot{W}$	1 hp = 745.7 W
		1 kW = 3415 Btu/h
		1 ft. lb$_f$/s = 1.3558 W
		1 Btu/h = 0.293 W
Pressure	p	1 lb$_f$/in.^{2} (psi) = 6894.8 Pa (N/m^2)
		1 in. Hg = 3,386 Pa
		1 atm = 101,325 Pa (N/m^2) = 14.696 psi
Radiation	l	1 langley = 41,860 J/m^2
		1 langley/min = 697.4 W/m^2
Specific heat capacity	c	1 Btu/lb$_m$ °F = 4187 J/kg K
Internal energy or enthalpy	e or h	1 Btu/lb$_m$ = 2326.0 J/kg
		1 cal/g = 4184 J/kg
Temperature	T	T(°R) = (9/5)T(K)
		T(°F) = [T(°C)](9/5) + 32
		T(°F) = [T(K) − 273.15](9/5) + 32
Thermal conductivity	k	1 Btu/h ft. °F = 1.731 W/m K
Thermal resistance	R_{th}	1 h °F/Btu = 1.8958 K/W
Velocity	V	1 ft./s = 0.3048 m/s
		1 mi/h = 0.44703 m/s
Viscosity, dynamic	μ	1 lb$_m$/ft. s = 1.488 N s/m^2
		1 cP = 0.00100 N s/m^2
Viscosity, kinematic	ν	1 ft.^{2}/s = 0.09029 m^2/s
		1 ft.^{2}/h = 2.581×10^{-5} m^2/s
Volume	V	1 ft.^{3} = 0.02832 m^3 = 28.32 L
		1 barrel = 42 gal (U.S.)
		1 gal (U.S. liq.) = 3.785 L
		1 gal (U.K.) = 4.546 L
Volumetric flow rate	$\dot{Q}$	1 ft.^{3}/min (cfia) = 0.000472 m^3/s
		1 gal/min (GPM) = 0.0631 l/s

A2

Solar Radiation Data

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The altitude and azimuth of the sun are given by

$$\sin \alpha = \sin L \sin \delta_s + \cos \phi \cos \delta_s \cos h_s \qquad (1)$$

and

$$\sin a_s = -\cos \delta_s \sin h_s / \cos \alpha \qquad (2)$$

where α = altitude of the sun (angular elevation above the horizon)
L = latitude of the observer
δ_s = declination of the sun
h_s = hour angle of sun (angular distance from the meridian of the observer)
a_s = azimuth of the sun (measured eastward from north)

From Eqs. (1) and (2) it can be seen that the altitude and azimuth of the sun are functions of the latitude of the observer, the time of day (hour angle), and the date (declination).

Figure A2.1(*b–g*) provides a series of charts, one for each 5° of latitude (except 5°, 15°, 75°, and 85°) giving the altitude and azimuth of the sun as a function of the true solar time and the declination of the sun in a form originally suggested by Hand. Linear interpolation for intermediate latitudes will give results within the accuracy to which the charts can be read.

On these charts, a point corresponding to the projected position of the sun is determined from the heavy lines corresponding to declination and solar time.

To find the solar altitude and azimuth:

1. Select the chart or charts appropriate to the latitude.
2. Find the solar declination δ corresponding to the date.
3. Determine the *true solar time* as follows:
   (a) To the *local standard time* (zone time) add 4′ for each degree of longitude the station is east of the standard meridian or subtract 4′ for each degree west of the standard meridian to get the *local mean solar time.*
   (b) To the *local mean solar time* add algebraically the equation of time; the sum is the required *true solar time.*
4. Read the required altitude and azimuth at the point determined by the declination and the true solar time. Interpolate linearly between two charts for intermediate latitudes.

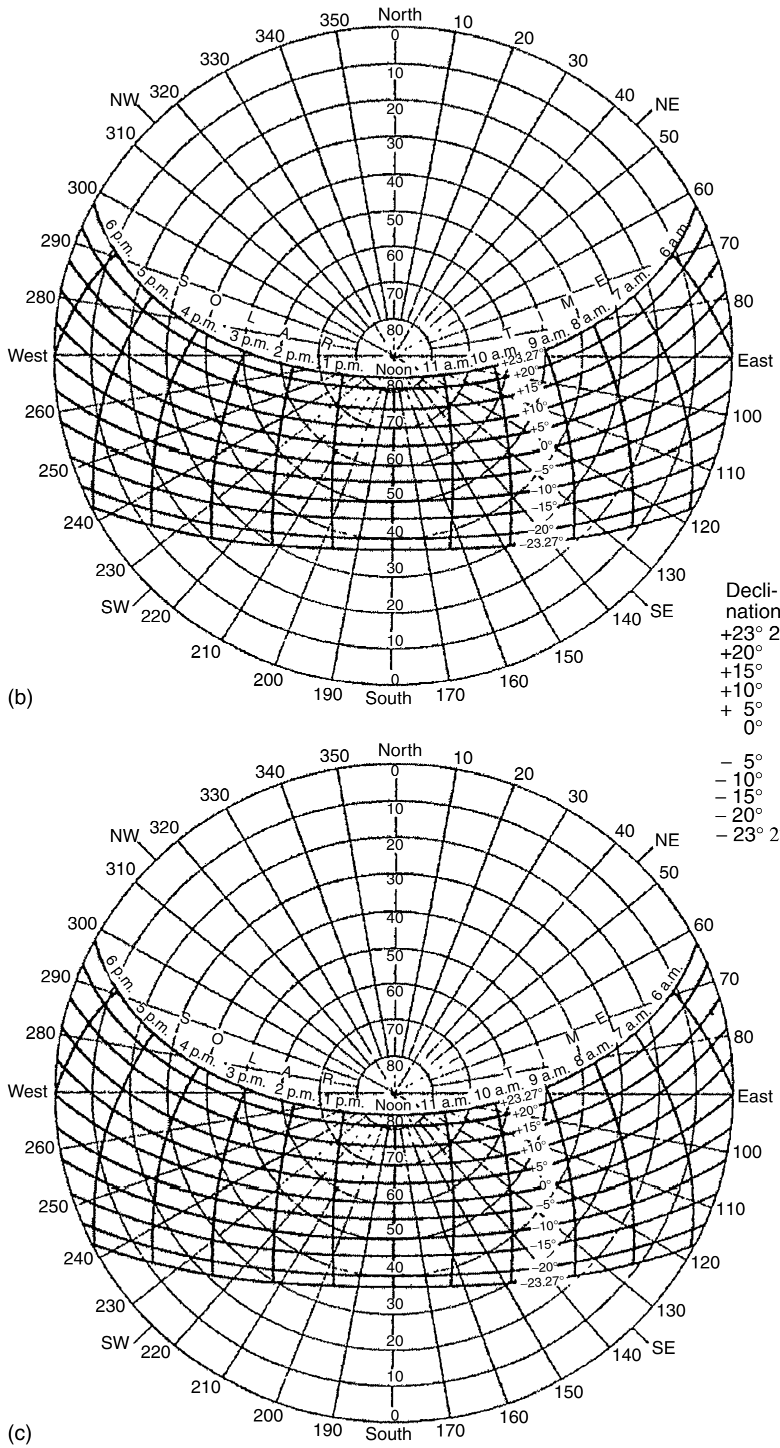
It should be emphasized that the solar altitude determined from these charts is the true geometric position of the center of the sun. At low solar elevations terrestrial refraction may considerably alter the apparent position of sun. Under average atmospheric refraction the sun will appear on the horizon when it actually is about 34′ below the horizon; the effect of refraction decreases rapidly with increasing solar elevation. Since sunset or sunrise is defined as the time when the upper limb of the sun appears on the horizon, and the semidiameter of the sun is 16′, sunset or sunrise occurs under average atmospheric refraction when the sun is 50′ below the horizon. In polar regions especially, unusual atmospheric refraction can make considerable variation in the time of sunset or sunrise.

The 90°N chart is included for interpolation purposes; the azimuths lose their directional significance at the pole.

Altitude and azimuth in southern latitudes. To compute solar altitude and azimuth for southern latitudes, change the sign of the solar declination and proceed as above. The resulting azimuths will indicate angular distance from *south* (measured eastward) rather than from north.

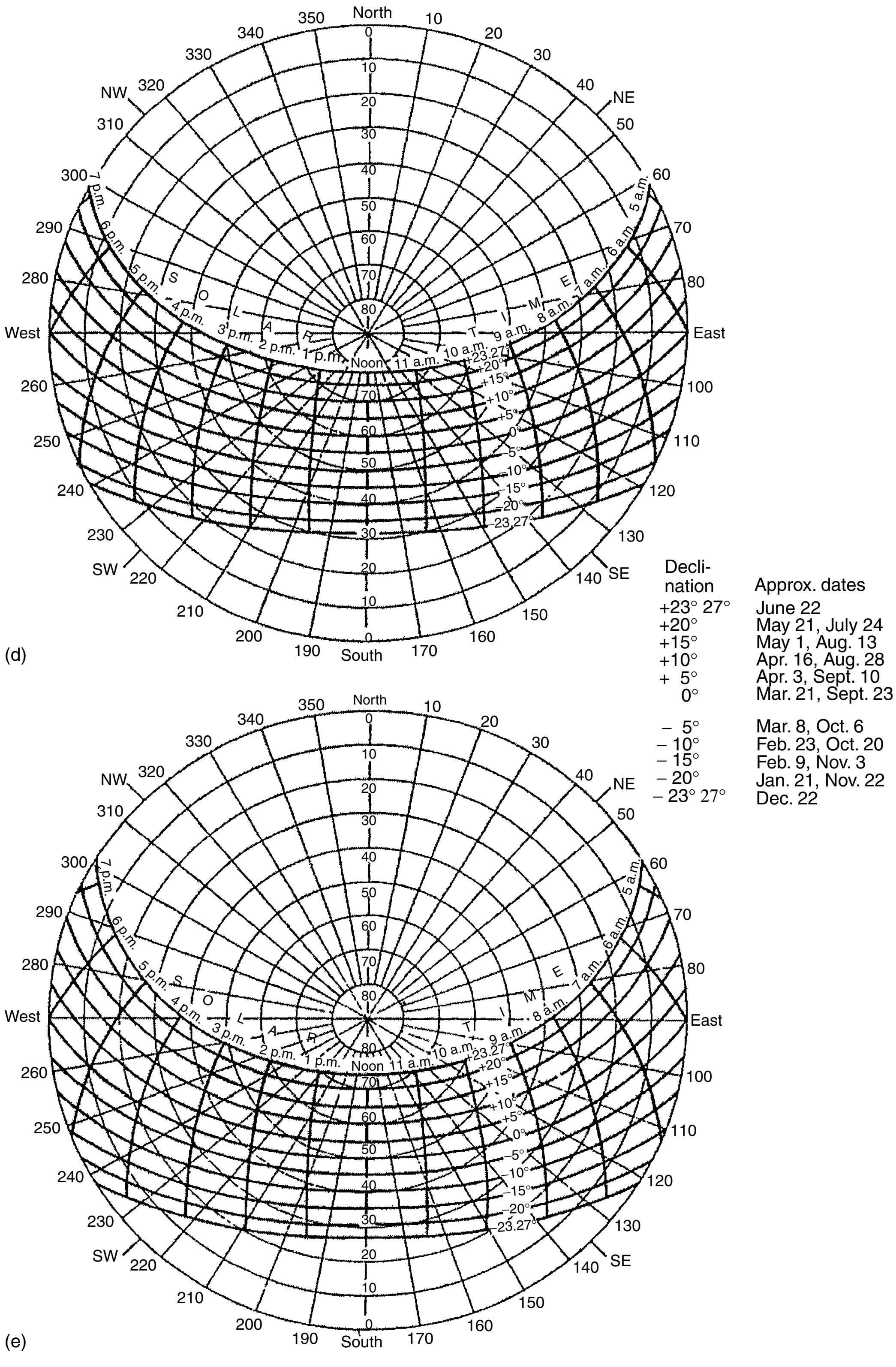
(a)

FIGURE A2.1 Description of method for calculating true solar time, together with accompanying meteorological charts, for computing solar-altitude and azimuth angles, (a) Description of method; (b) chart, 25°N latitude; (c) chart, 30°N latitude; (d) chart, 35°N latitude; (e) chart, 40°N latitude; (f) chart, 45°N latitude; (g) chart, 50°N latitude. Description and charts reproduced from the "Smithsonian Meteorological Tables" with permission from the Smithsonian Institute, Washington, D.C.



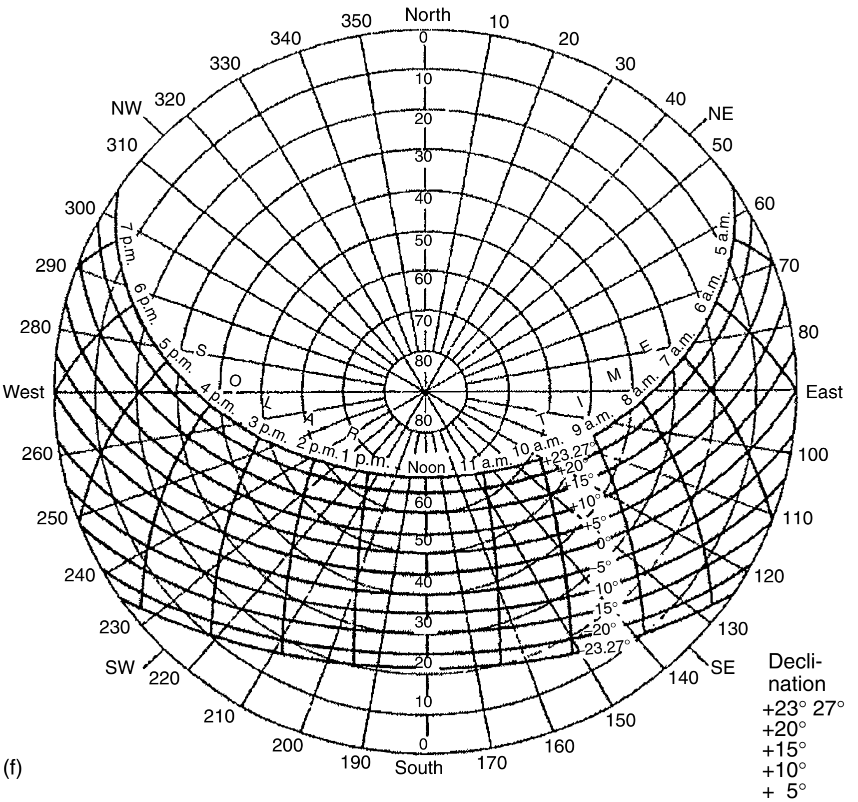
Declination	Approx. dates
+23° 27°	June 22
+20°	May 21, July 24
+15°	May 1, Aug. 13
+10°	Apr. 16, Aug. 28
+ 5°	Apr. 3, Sept. 10
0°	Mar. 21, Sept. 23
– 5°	Mar. 8, Oct. 6
– 10°	Feb. 23, Oct. 20
– 15°	Feb. 9, Nov. 3
– 20°	Jan. 21, Nov. 22
– 23° 27°	Dec. 22

FIGURE A2.1 (*continued*)



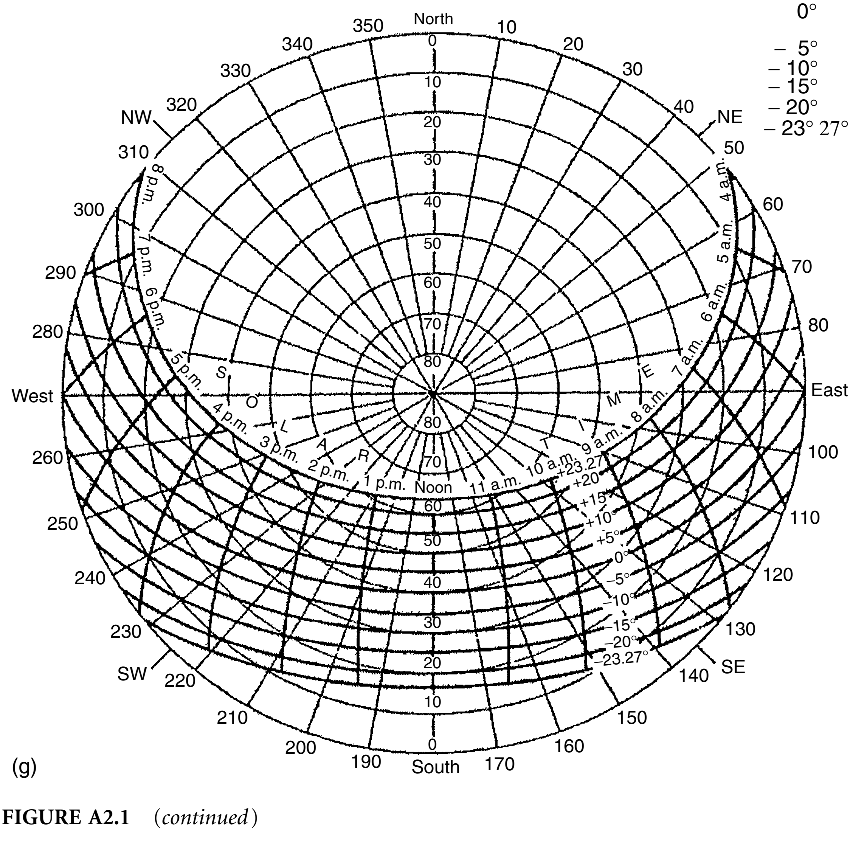
Declination	Approx. dates
+23° 27°	June 22
+20°	May 21, July 24
+15°	May 1, Aug. 13
+10°	Apr. 16, Aug. 28
+ 5°	Apr. 3, Sept. 10
0°	Mar. 21, Sept. 23
− 5°	Mar. 8, Oct. 6
− 10°	Feb. 23, Oct. 20
− 15°	Feb. 9, Nov. 3
− 20°	Jan. 21, Nov. 22
− 23° 27°	Dec. 22

FIGURE A2.1 *(continued)*



(f)

Declination	Approx. dates
+23° 27°	June 22
+20°	May 21, July 24
+15°	May 1, Aug. 13
+10°	Apr. 16, Aug. 28
+ 5°	Apr. 3, Sept. 10
0°	Mar. 21, Sept. 23
– 5°	Mar. 8, Oct. 6
– 10°	Feb. 23, Oct. 20
– 15°	Feb. 9, Nov. 3
– 20°	Jan. 21, Nov. 22
– 23° 27°	Dec. 22



(g)

FIGURE A2.1 (*continued*)

TABLE A2.1 Solar Irradiance for Different Air Masses

Wavelength	Air Mass; $\alpha = 0.66$; $\beta = 0.085$[a]				
	0	1	4	7	10
0.290	482.0	0.0	0.0	0.0	0.0
0.295	584.0	0.0	0.0	0.0	0.0
0.300	514.0	4.1	0.0	0.0	0.0
0.305	603.0	11.4	0.0	0.0	0.0
0.310	689.0	30.5	0.0	0.0	0.0
0.315	764.0	79.4	0.1	0.0	0.0
0.320	830.0	202.6	2.9	0.0	0.0
0.325	975.0	269.5	5.7	0.1	0.0
0.330	1059.0	331.6	10.2	0.3	0.0
0.335	1081.0	383.4	17.1	0.8	0.0
0.340	1074.0	431.3	24.9	1.8	0.1
0.345	1069.0	449.2	33.3	2.5	0.2
0.350	1093.0	480.5	40.8	3.5	0.3
0.355	1083.0	498.0	48.4	4.7	0.5
0.360	1068.0	513.7	57.2	6.4	0.7
0.365	1132.0	561.3	68.4	8.3	1.0
0.370	1181.0	603.5	80.5	10.7	1.4
0.375	1157.0	609.4	89.0	13.0	1.9
0.380	1120.0	608.0	97.2	15.6	2.5
0.385	1098.0	609.8	104.5	17.9	3.1
0.390	1098.0	623.9	114.5	21.0	3.9
0.395	1189.0	691.2	135.8	26.7	5.2
0.400	1429.0	849.9	178.8	37.6	7.9
0.405	1644.0	992.8	218.7	48.2	10.6
0.410	1751.0	1073.7	247.5	57.1	13.2
0.415	1774.0	1104.5	266.5	64.3	15.5
0.420	1747.0	1104.3	278.9	70.4	17.8
0.425	1693.0	1086.5	287.2	78.9	20.1
0.430	1639.0	1067.9	295.4	81.7	22.6
0.435	1663.0	1100.1	318.4	92.2	26.7
0.440	1810.0	1215.5	368.2	111.5	33.8
0.445	1922.0	1310.4	415.3	131.6	41.7
0.450	2006.0	1388.4	460.3	152.6	50.6
0.455	2057.0	1434.8	486.9	165.2	56.1
0.460	2066.0	1452.2	504.4	175.2	60.8
0.465	2048.0	1450.7	515.7	183.3	65.1
0.470	2033.0	1451.2	527.9	192.0	69.8
0.475	2044.0	1470.3	547.3	203.7	75.8
0.480	2074.0	1503.4	572.6	218.1	83.1
0.485	1976.0	1443.3	562.4	219.2	85.4
0.490	1950.0	1435.2	572.2	228.2	91.0
0.495	1960.0	1453.6	592.9	241.9	98.7
0.500	1942.0	1451.2	605.6	252.7	105.5
0.505	1920.0	1440.1	607.6	256.4	108.2
0.510	1882.0	1416.8	604.4	257.8	110.0
0.515	1833.0	1384.9	597.3	257.6	111.1
0.520	1833.0	1390.0	606.1	264.3	115.2
0.525	1852.0	1409.5	621.3	273.9	120.7
0.530	1842.0	1406.9	626.9	279.4	124.5
0.535	1818.0	1393.6	627.7	282.8	127.4
0.540	1783.0	1371.7	624.5	284.4	129.5
0.545	1754.0	1354.2	623.2	286.8	132.0
0.550	1725.0	1336.6	621.7	289.2	134.5
0.555	1720.0	1335.7	625.5	293.0	137.3

(continued)

TABLE A2.1 ***(Continued)***

Wavelength	Air Mass; $\alpha = 0.66$; $\beta = 0.085$[a]				
	0	1	4	7	10
0.560	1695.0	1319.2	622.0	293.3	138.3
0.565	1705.0	1330.0	631.3	299.6	142.2
0.570	1712.0	1338.4	639.5	305.6	146.0
0.575	1719.0	1346.9	647.8	311.6	149.6
0.580	1715.0	1346.7	652.0	315.7	152.8
0.585	1712.0	1347.3	656.6	320.0	156.0
0.590	1700.0	1340.7	657.7	322.6	158.3
0.595	1682.0	1329.4	656.4	324.1	160.0
0.600	1660.0	1319.6	655.8	325.9	162.0
0.605	1647.0	1311.0	661.3	333.6	168.2
0.610	1635.0	1307.9	669.6	342.8	175.5
0.620	1602.0	1294.2	682.4	359.9	189.7
0.630	1570.0	1280.9	695.6	377.8	205.2
0.640	1544.0	1272.1	711.4	397.9	222.5
0.650	1511.0	1257.1	723.9	416.9	240.1
0.660	1486.0	1244.2	730.2	428.6	251.6
0.670	1456.0	1226.8	733.8	438.9	262.5
0.680	1427.0	1209.9	737.4	449.5	273.9
0.690	1402.0	1196.2	742.9	461.3	286.5
0.698	1374.6	1010.3	546.1	311.8	181.6
0.700	1369.0	1175.3	743.7	470.6	297.7
0.710	1344.0	1157.4	739.2	472.1	301.5
0.720	1314.0	1135.1	731.7	471.6	304.0
0.728	1295.5	1003.1	582.3	351.7	212.5
0.730	1290.0	1117.8	727.1	479.0	307.7
0.740	1260.0	1095.1	718.9	471.9	309.8
0.750	1235.0	1076.6	713.2	472.4	313.0
0.762	1205.5	794.0	357.1	163.6	69.1
0.770	1185.0	1039.2	700.8	472.7	318.8
0.780	1159.0	1019.4	693.6	472.0	321.1
0.790	1134.0	1000.3	686.7	471.4	323.6
0.800	1109.0	981.2	679.4	470.5	325.8
0.806	1095.1	874.4	547.7	355.9	234.4
0.825	1048.0	931.6	654.3	459.6	322.8
0.830	1036.0	921.8	649.3	457.3	322.1
0.835	1024.5	912.4	644.4	455.2	321.5
0.846	998.1	476.2	181.0	85.9	44.2
0.860	968.0	506.4	212.0	107.4	58.3
0.870	947.0	453.8	174.7	84.0	43.8
0.875	436.5	449.2	173.4	83.6	43.7
0.887	912.5	448.6	178.3	87.7	46.7
0.900	891.0	448.9	183.7	92.3	50.0
0.907	882.8	455.2	190.9	97.6	53.7
0.915	874.5	461.5	198.5	103.2	57.5
0.925	863.5	279.0	73.6	28.0	12.1
0.930	858.0	221.8	46.9	15.4	6.0
0.940	847.0	313.4	95.0	39.6	18.5
0.950	837.0	296.5	86.3	35.0	16.0
0.955	828.5	321.1	102.3	44.1	21.2
0.965	811.5	344.4	120.4	55.1	27.8
0.975	794.0	576.9	346.0	224.6	150.1
0.985	776.0	544.6	316.1	201.2	132.4
1.018	719.2	617.5	391.0	247.5	156.7
1.082	620.0	512.9	290.4	164.4	93.1

(continued)

TABLE A2.1 ***(Continued)***

Wavelength	Air Mass; $\alpha = 0.66$; $\beta = 0.085$[a]				
	0	1	4	7	10
1.094	602.0	464.1	303.1	210.8	149.9
1.098	596.0	503.7	304.1	183.6	110.9
1.101	591.8	504.8	362.7	267.3	198.8
1.128	560.5	135.1	27.7	9.1	3.6
1.131	557.0	152.2	35.3	12.6	5.3
1.137	550.1	143.1	31.7	11.0	4.5
1.144	542.0	191.2	57.4	24.2	11.6
1.147	538.5	174.5	48.2	19.3	8.8
1.178	507.0	399.3	195.1	95.4	46.6
1.189	496.0	402.2	214.5	114.4	61.0
1.193	492.0	424.0	310.8	233.3	176.6
1.222	464.3	391.8	235.3	141.3	84.9
1.236	451.2	390.8	254.1	165.2	107.4
1.264	426.5	329.2	209.7	140.0	94.3
1.276	416.7	342.6	238.6	172.6	126.3
1.288	406.8	347.3	216.1	134.4	83.7
1.314	386.1	298.3	137.6	63.5	29.3
1.335	369.7	190.6	85.0	46.7	27.7
1.384	343.7	5.7	0.1	0.0	0.0
1.432	321.0	44.6	5.4	1.3	0.4
1.457	308.6	85.4	20.6	7.7	3.3
1.472	301.4	77.4	17.4	6.2	2.6
1.542	270.4	239.3	165.9	115.0	79.7
1.572	257.3	222.6	168.1	130.4	102.1
1.599	245.4	216.0	166.7	131.5	104.5
1.608	241.5	208.5	157.4	122.1	95.7
1.626	233.6	206.7	160.7	127.5	101.9
1.644	225.6	197.9	152.4	120.1	95.5
1.650	223.0	195.7	150.9	119.1	94.7
1.676	212.1	181.9	114.8	72.4	45.7
1.732	187.9	161.5	102.5	65.1	41.3
1.782	166.6	136.7	75.6	41.8	23.1
1.862	138.2	4.0	0.1	0.0	0.0
1.955	112.9	42.7	14.5	6.8	3.6
2.008	102.0	69.4	35.8	17.7	6.4
2.014	101.2	74.7	45.5	28.8	17.8
2.057	95.6	69.5	41.3	25.3	14.8
2.124	87.4	70.0	35.9	18.4	9.5
2.156	83.8	66.0	32.3	15.8	7.7
2.201	78.9	66.1	49.1	38.0	29.7
2.266	72.4	61.6	46.8	36.8	29.3
2.320	67.6	57.2	43.2	33.8	26.8
2.338	66.3	54.7	39.9	30.4	23.4
2.356	65.1	52.0	36.3	26.5	19.6
2.388	62.8	36.0	18.7	11.7	7.8
2.415	61.0	32.5	15.8	9.4	6.0
2.453	58.3	29.6	13.7	7.9	5.0
2.494	55.4	20.3	6.8	3.2	1.7
2.537	52.4	4.6	0.4	0.1	0.0
2.900	35.0	2.9	0.2	0.0	0.0
2.941	33.4	6.0	1.0	0.3	0.1
2.954	32.8	5.7	0.9	0.3	0.1
2.973	32.1	8.7	2.2	0.9	0.4
3.005	30.8	7.8	1.8	0.7	0.3

(continued)

TABLE A2.1 ***(Continued)***

Wavelength	Air Mass; $\alpha = 0.66$; $\beta = 0.085$[a]				
	0	1	4	7	10
3.045	28.8	4.7	0.7	0.2	0.1
3.056	28.2	4.9	0.8	0.2	0.1
3.097	26.2	3.2	0.4	0.1	0.0
3.132	24.9	6.8	1.7	0.7	0.3
3.156	24.1	18.7	12.6	8.9	6.3
3.204	22.5	2.1	0.2	0.0	0.0
3.214	22.1	3.4	0.5	0.1	0.0
3.245	21.1	3.9	0.7	0.2	0.1
3.260	20.6	3.7	0.6	0.2	0.1
3.285	19.7	14.2	8.5	5.1	2.8
3.317	18.8	12.9	6.9	3.5	1.3
3.344	18.1	4.2	0.9	0.3	0.1
3.403	16.5	12.3	7.8	5.1	3.2
3.450	15.6	12.5	8.9	6.7	5.0
3.507	14.5	12.5	9.9	8.1	6.7
3.538	14.2	11.8	8.8	6.9	5.5
3.573	13.8	10.9	5.4	2.6	1.3
3.633	13.1	10.8	8.3	6.7	5.5
3.673	12.6	9.1	6.1	4.6	3.5
3.696	12.3	10.4	8.2	6.7	5.6
3.712	12.2	10.9	9.0	7.6	6.5
3.765	11.5	9.5	7.2	5.9	4.8
3.812	11.0	8.9	6.7	5.4	4.4
3.888	10.4	8.1	5.6	4.0	2.9
3.923	10.1	8.0	5.6	4.2	3.1
3.948	9.9	7.8	5.5	4.0	3.0
4.045	9.1	6.7	4.1	2.6	1.5
Total Wm^3	1353	889.2	448.7	255.2	153.8

W/m^2 μm; H_2O 20 mm; O_3 3.4 mm.

[a] The parameters α and β are measures of turbidity of the atmosphere. They are used in the atmospheric transmittance equation $\bar{\tau}_{\text{atm}} = e^{-(C_1+C_2)m}$; C_1 includes Rayleigh and ozone attenuation; $C_2 \equiv \beta/\lambda^{a}$.

Source: From Thekaekara, M. P. 1974. *The Energy Crisis and Energy from the Sun.* Institute for Environmental Sciences.

TABLE A2.2 Monthly Averaged, Daily Extraterrestrial Insolation on a Horizontal Surface (Units: Wh/m^2)

Latitude (deg)	January	February	March	April	May	June	July	August	September	October	November	December
20	7415	8397	9552	10,422	10,801	10,868	10,794	10,499	9791	8686	7598	7076
25	6656	7769	9153	10,312	10,936	11,119	10,988	10,484	9494	8129	6871	6284
30	5861	7087	8686	10,127	11,001	11,303	11,114	10,395	9125	7513	6103	5463
35	5039	6359	8153	9869	10,995	11,422	11,172	10,233	8687	6845	5304	4621
40	4200	5591	7559	9540	10,922	11,478	11,165	10,002	8184	6129	4483	3771
45	3355	4791	6909	9145	10,786	11,477	11,099	9705	7620	5373	3648	2925
50	2519	3967	6207	8686	10,594	11,430	10,981	9347	6998	4583	2815	2100
55	1711	3132	5460	8171	10,358	11,352	10,825	8935	6325	3770	1999	1320
60	963	2299	4673	7608	10,097	11,276	10,657	8480	5605	2942	1227	623
65	334	1491	3855	7008	9852	11,279	10,531	8001	4846	2116	544	97

TABLE A2.3a Worldwide Global Horizontal Average Solar Radiation (Units: MJ/sq.m-day)

Position	Lat	Long	January	February	March	April	May	June	July	August	September	October	November	December
Argentina														
Buenos Aires	34.58 S	58.48 W	24.86	21.75	18.56	11.75	8.71	7.15	7.82	8.75	14.49	16.66	24.90	21.93
Australia														
Adelaide	34.93 S	138.52 E	20.99	17.50	20.15	18.27	17.98	—	18.81	19.64	20.11	20.88	20.57	20.72
Brisbane	27.43 S	153.08 E	25.36	22.22	13.25	16.61	12.23	11.52	9.70	15.10	17.61	19.89	—	—
Canberra	35.30 S	148.18 E	28.20	24.68	20.56	14.89	10.29	6.62	—	12.33	16.88	24.06	26.00	25.77
Darwin	12.47 S	130.83 E	26.92	23.40	18.13	13.62	9.30	7.89	9.41	11.15	14.85	18.87	23.43	22.34
Hobart	42.88 S	147.32 E	—	—	—	10.09	7.26	6.04	5.72	9.21	13.54	18.12	—	—
Laverton	37.85 S	114.08 E	22.96	20.42	15.59	13.40	7.48	6.10	6.54	10.43	13.24	18.76	—	—
Sydney	33.87 S	151.20 E	21.09	21.75	17.63	13.63	9.78	8.79	7.62	12.84	16.93	22.10	—	—
Austria														
Wien	48.20 N	16.57 E	3.54	7.10	8.05	14.72	16.79	20.87	19.89	17.27	12.55	8.45	3.51	2.82
Innsbruck	47.27 N	11.38 E	5.57	9.28	10.15	15.96	14.57	17.65	18.35	17.26	12.98	9.08	4.28	3.50
Barbados														
Husbands	13.15 N	59.62 W	19.11	20.23	—	21.80	19.84	20.86	21.55	22.14	—	—	18.30	16.56
Belgium														
Ostende	51.23 N	2.92 E	2.82	5.75	9.93	15.18	16.74	16.93	18.21	18.29	11.71	6.15	2.69	1.97
Melle	50.98 N	3.83 E	2.40	4.66	8.41	13.55	14.23	13.28	15.71	15.61	10.63	5.82	2.40	1.59
Brunei														
Brunei	4.98 N	114.93 E	19.46	20.12	22.71	20.54	19.74	18.31	19.38	20.08	20.83	17.51	17.39	18.12
Bulgaria														
Chirpan	42.20 N	25.33 E	6.72	6.79	8.54	13.27	17.25	17.39	19.85	14.61	12.53	8.52	5.08	5.09
Sofia	42.65 N	23.38 E	4.05	6.23	7.93	9.36	12.98	19.73	19.40	17.70	14.71	6.44	—	3.14
Canada[a]														
Montreal	45.47 N	73.75 E	4.74	8.33	11.84	10.55	15.05	22.44	21.08	18.67	14.83	9.18	4.04	4.01
Ottawa	45.32 N	75.67 E	5.34	9.59	13.33	13.98	20.18	20.34	19.46	17.88	13.84	7.38	4.64	5.04
Toronto	43.67 N	79.38 E	4.79	8.15	11.96	14.00	18.16	24.35	23.38	—	15.89	9.40	4.72	3.79
Vancouver	49.18 N	123.17 E	3.73	4.81	12.14	16.41	20.65	24.04	22.87	19.08	12.77	7.39	4.29	1.53
Chile														
Pascua	27.17 S	109.43 W	19.64	16.65	—	11.12	9.52	8.81	10.90	12.29	17.19	20.51	21.20	22.44
Santiago	33.45 S	70.70 W	18.61	16.33	13.44	8.32	5.07	3.66	3.35	5.65	8.15	13.62	20.14	23.88
China														
Beijing	39.93 N	116.28 W	7.73	10.59	13.87	17.93	20.18	18.65	15.64	16.61	15.52	11.29	7.25	6.89
Guangzhou	23.13 N	113.32 E	11.01	6.32	4.04	7.89	10.53	12.48	16.14	16.02	15.03	15.79	11.55	9.10

(continued)

TABLE A2.3a *(Continued)*

Position	Lat	Long	January	February	March	April	May	June	July	August	September	October	November	December
Harbin	45.75 N	126.77 E	5.15	9.54	17.55	20.51	20.33	17.85	19.18	16.09	13.38	14.50	10.50	6.98
Kunming	25.02 N	102.68 E	9.92	11.26	14.38	18.00	18.53	17.37	11.95	18.47	15.94	12.45	11.96	13.62
Lanzhou	36.05 N	103.88 E	7.30	12.47	10.62	18.91	17.40	20.40	20.23	17.37	13.23	10.21	8.22	6.43
Shanghai	31.17 N	121.43 E	7.44	10.31	11.78	14.36	14.23	16.79	14.63	11.85	15.96	12.03	7.73	8.70
Columbia														
Bogota	4.70 N	74.13 W	17.89	—	19.37	16.58	14.86	—	15.42	18.20	17.05	14.58	14.20	16.66
Cuba														
Havana	23.17 N	82.35 W	—	14.70	18.94	20.95	22.63	18.83	21.40	20.19	16.84	16.98	13.19	13.81
Czech														
Kucharovice	48.88 N	16.08 E	3.03	5.85	9.88	14.06	20.84	19.24	21.18	19.41	13.61	6.11	3.47	2.12
Churanov	49.07 N	13.62 E	2.89	5.82	9.24	13.18	21.32	15.68	20.51	19.49	12.84	5.68	3.36	2.99
Hradec Kralov	50.25 N	15.85 E	3.51	5.94	10.58	15.95	20.42	18.43	17.17	17.92	11.86	6.27	2.45	1.89
Denmark														
Copenhagen	55.67 N	12.30 E	1.83	3.32	7.09	11.12	21.39	24.93	—	13.92	10.10	5.20	2.81	1.23
Egypt														
Cairo	30.08 N	31.28 E	10.06	12.96	18.49	23.04	21.91	26.07	25.16	23.09	21.01	—	11.74	9.85
Mersa Matruh	31.33 N	27.22 E	8.38	11.92	18.47	24.27	24.17	—	26.67	26.27	21.92	18.28	11.71	8.76
Ethiopia														
Addis Ababa	8.98 N	38.80 E	—	11.39	—	12.01	—	—	—	6.33	9.35	11.71	11.69	11.50
Fiji														
Nandi	17.75 S	177.45 E	20.82	20.65	20.25	18.81	15.68	14.18	15.08	16.71	19.37	20.11	21.78	25.09
Suva	48.05 S	178.57 E	20.37	17.74	16.22	13.82	10.81	12.48	11.40	—	—	18.49	19.96	20.99
Finland														
Helsinki	60.32 N	24.97 E	1.13	2.94	5.59	11.52	17.60	16.81	20.66	15.44	8.44	3.31	0.97	0.63
France														
Agen	44.18 N	0.60 E	4.83	7.40	10.69	17.12	19.25	20.42	21.63	20.64	15.56	8.41	5.09	5.01
Nice	43.65 N	7.20 E	6.83		11.37	17.79	20.74	24.10	24.85	24.86	15.04	10.99	7.08	6.73
Paris	48.97 N	2.45 E	2.62	5.08	7.21	12.90	14.84	13.04	15.54	16.30	10.17	5.61	3.14	2.20
Germany														
Bonn	50.70 N	7.15 E	2.94	5.82	8.01	14.27	15.67	14.41	18.57	17.80	11.70	6.15	3.42	1.90
Nuremberg	53.33 N	13.20 E	3.23	6.92	9.08	15.69	15.71	18.21	21.14	17.98	12.43	8.15	2.79	2.51
Bremen	53.05 N	8.80 E	2.36	4.93	8.53	14.52	14.94	14.52	19.40	15.02	10.48	6.27	2.80	1.66
Hamburg	53.63 N	10.00 E	1.97	3.96	7.59	12.32	14.11	12.69	19.00	14.11	10.29	6.45	2.33	1.43
Stuttgart	48.83 N	9.20 E	3.59	7.18	9.22	15.81	17.72	17.44	22.21	19.87	12.36	7.81	3.19	2.54
Ghana														
Bole	9.03 N	2.48 W	18.29	19.76	19.71	19.15	16.61	—	—	13.68	16.29	17.27	17.33	15.93

Accra	5.60 N	0.17 W	14.82	16.26	18.27	16.73	18.15	13.96	13.86	13.49	15.32	19.14	18.16	14.23
Great Britain														
Belfast	54.65 N	6.22 W	2.00	3.60	6.85	12.00	15.41	15.09	15.46	13.56	11.49	4.63	2.34	1.24
Jersey	49.22 N	2.20 W	2.76	5.65	9.51	14.98	18.51	17.83	18.14	18.62	12.98	6.16	3.26	2.83
London	51.52 N	0.12 W	2.24	3.87	7.40	12.01	12.38	13.24	16.59	16.23	12.59	5.67	2.87	1.97
Greece														
Athens	37.97 N	23.72 E	9.11	10.94	15.70	20.91	23.85	25.48	24.21	23.08	19.03	13.29	5.98	6.64
Sikiwna	37.98 N	22.73 E	7.60	8.16	11.99	21.06	22.62	24.32	23.56	21.73	17.30	11.75	9.45	6.35
Guadeloupe														
Le Raizet	16.27 N	61.52 W	14.88	18.10	20.55	19.69	20.26	20.65	20.65	20.24	18.47	17.79	13.49	14.38
Guyana														
Cayenne	4.83 N	52.37 W	14.46	14.67	16.28	17.57	—	14.92	17.42	18.24	20.52	—	22.69	17.04
Hong Kong														
King's Park	22.32 N	114.17 W	12.34	7.39	6.94	9.50	11.38	13.60	16.70	17.06	15.91	16.52	14.19	10.00
Hungary														
Budapest	47.43 N	19.18 E	2.61	7.46	11.14	14.46	20.69	19.47	21.46	19.72	12.88	7.96	2.95	2.47
Iceland														
Reykjavik	64.13 N	21.90 W	0.52	2.02	6.25	11.77	13.07	14.58	16.83	11.35	9.70	3.18	1.00	0.65
India														
Bombay	19.12 N	72.85 E	18.44	21.00	22.72	24.52	24.86	19.75	15.84	16.00	18.19	20.38	19.18	17.81
Calcutta	22.53 N	88.33 E	15.69	18.34	20.09	22.34	22.37	17.55	17.07	16.55	16.52	16.90	16.35	15.00
Madras	13.00 N	80.18 E	19.09	22.71	25.14	24.88	23.89	—	18.22	19.68	19.S1	16.41	14.76	15.79
Nagpur	21. 10 N	79.05 E	18.08	21.01	22.25	24.08	24.79	19.84	15.58	15.47	17.66	20.10	18.98	17.33
New Delhi	28.58 N	77.20 E	14.62	18.25	20.15	23.40	23.80	19.16	20.20	19.89	20.08	19.74	16.95	14.22
Ireland														
Dublin	53.43 N	6.25 W	2.51	4.75	7.48	11.06	17.46	19.11	15.64	13.89	9.65	5.77	2.93	—
Israel														
Jerusalem	31.78 N	35.22 E	10.79	13.01	18.08	23.79	29.10	31.54	31.83	28.79	25.19	20.26	12.61	10.71
Italy														
Milan	45.43 N	9.28 E	—	6.48	10.09	13.17	17.55	16.32	18.60	16.86	11.64	5.40	3.52	2.41
Rome	41.80 N	12.55 E	—	9.75	13.38	15.82	15.82	18.89	22.27	21.53	16.08	8.27	6.41	4.49
Japan														
Fukuoka	33.58 N	130.38 E	8.11	8.72	10.95	13.97	14.36	12.81	13.84	16.75	13.92	11.86	10.05	7.30
Tateno	36.05 N	140.13 E	9.06	12.17	11.00	15.78	16.52	15.26	—	—	—	9.60	8.55	8.26
Yonago	35.43 N	133.35 E	6.25	7.16	10.87	17.30	16.72	15.44	17.06	19.93	12.41	10.82	7.50	5.51
Kenya														
Mombasa	4.03 S	39.62 E	22.30	22.17	22.74	18.49	18.31	17.41	—	18.12	21.03	22.97	21.87	21.25
Nairobi	1.32 S	36.92 E	—	24.10	21.20	18.65	14.83	15.00	13.44	14.12	19.14	19.38	16.90	18.27

(continued)

TABLE A2.3a ***(Continued)***

Position	Lat	Long	January	February	March	April	May	June	July	August	September	October	November	December
Lithuania														
Kaunas	54.88 N	23.88 E	1.89	4.43	7.40	12.97	18.88	18.74	21.41	15.79	10.40	5.64	1.80	1.10
Madagascar														
Antanarivo	18.80 S	47.48 E	15.94	13.18	13.07	11.53	9.25	8.21	9.32	—	—	16.43	15.19	15.62
Malaysia														
Kualalumpur	3.12 N	101.55 E	15.36	17.67	18.48	16.87	15.67	16.24	15.32	15.89	14.62	14.13	13.54	11.53
Piang	5.30 N	100.27 E	19.47	21.35	23.24	20.52	18.63	19.32	17.17	16.96	15.93	16.01	18.35	17.37
Martinique														
Le Lamentin	14.60 N	61.00 W	17.76	20.07	22.53	21.95	22.42	21.23	20.86	21.84	20.23	19.87	14.08	16.25
Mexico														
Chihuahua	28.63 N	106.08 W	14.80	—	—	—	26.94	26.28	24.01	24.22	20.25	19.55	10.57	15.79
Orizabita	20.58 N	99.20 E	19.49	23.07	27.44	27.35	26.04	25.05	—	27.53	21.06	17.85	15.48	12.93
Mongolia														
Ulan Bator	47.93 N	106.98 E	6.28	9.22	14.34	18.18	20.50	19.34	16.34	16.65	14.08	11.36	7.19	5.35
Uliasutai	47.75 N	96.85 E	6.43	10.71	14.83	20.32	23.86	20.46	21.66	17.81	15.97	10.92	7.32	5.08
Morocco														
Casablanca	33.57 N	7.67 E	11.46	12.70	15.93	21.25	24.45	25.27	25.53	23.60	19.97	14.68	11.61	9.03
Mozambique														
Maputo	25.97 S	32.60 E	26.35	23.16	19.33	20.54	16.33	14.17	—	—	—	22.55	25.48	26.19
Netherlands														
Maastricht	50.92 N	5.78 E	3.20	5.43	8.48	14.82	14.97	14.32	18.40	17.51	11.65	6.51	3.01	1.72
New Caledonia														
Koumac	20.57 S	164.28 E	24.89	21.15	16.96	18.98	15.67	14.55	15.75	17.62	22.48	15.83	27.53	26.91
New Zealand														
Wilmington	41.28 S	174.77 E	22.59	19.67	14.91	9.52	6.97	4.37	5.74	7.14	12.50	16.34	19.07	24.07
Christchurch	43.48 S	172.55 E	23.46	19.68	13.98	8.96	6.47	4.74	5.38	6.94	13.18	17.45	18.91	24.35
Nigeria														
Benin City	6.32 N	5.60 E	14.89	17.29	19.15	17.21	16.97	15.04	10.24	12.54	14.37	15.99	17.43	15.75
Norway														
Bergen	60.40 N	5.32 E	0.46	1.33	3.18	8.36	19.24	16.70	16.28	10.19	6.53	3.19	1.36	0.35
Oman														
Seeb	23.58 N	58.28 E	12.90	14.86	21.22	22.22	25.30	24.02	23.46	21.66	20.07	18.45	15.49	13.12
Salalah	17.03 N	54.08 E	16.52	16.92	18.49	20.65	21.46	16.92	8.52	11.41	17.14	18.62	16.42	—
Pakistan														
Karachi	24.90 N	67.13 E	13.84	—	—	19.69	20.31	16.62	—	—	—	—	12.94	11.07
Multan	30.20 N	71.43 E	12.29	15.86	18.33	22.35	22.57	21.65	20.31	20.44	20.57	15.91	12.68	10.00

Islamabad	33.62 N	73.10 E	10.38	12.42	16.98	22.65	—	25.49	20.64	18.91	14.20	15.30	10.64	8.30
Peru														
Puno	15.83 S	70.02 W	14.98	12.92	16.08	20.03	17.45	17.42	15.74	15.32	16.11	16.18	14.24	13.90
Poland														
Warszawa	52.28 N	20.97 E	1.73	3.83	7.81	10.53	19.22	17.11	20.18	15.00	10.65	4.95	2.39	1.68
Kolobrzeg	54.18 N	15.58 E	2.50	3.25	8.86	15.21	20.79	20.50	17.19	16.46	7.95	5.75	1.78	1.18
Portugal														
Evora	38.57 N	7.90 W	9.92	12.43	17.81	18.69	23.57	29.23	28.75	23.77	20.17	—	6.81	4.57
Lisbon	38.72 N	9.15 W	9.24	11.60	17.52	18.49	24.64	29.02	28.14	22.20	19.76	13.56	7.18	4.83
Romania														
Bucuresti	44.50 N	26.13 E	7.05	10.22	12.04	16.53	18.97	22.16	23.19	—	17.17	9.55	4.82	—
Constania	44.22 N	28.63 E	5.62	9.28	14.31	20.59	23.23	25.80	27.98	24.22	16.91	11.89	6.19	5.10
Galati	45.50 N	28.02 E	6.09	9.33	14.31	17.75	21.77	22.74	25.55	19.70	14.05	11.26	6.32	5.38
Russia														
Alexandovsko	60.38 N	77.87 E	1.34	4.17	9.16	17.05	21.83	21.34	20.26	13.05	10.16	4.68	1.71	0.68
Moscow	55.75 N	37.57 E	1.45	3.96	8.09	11.69	18.86	18.12	17.51	14.17	10.92	4.03	2.28	1.29
St. Petersburg	59.97 N	30.30 E	1.03	3.11	4.88	12.24	20.59	21.55	20.43	13.27	7.83	2.93	1.16	0.59
Verkhoyansk	67.55 N	133.38 E	0.21	2.25	7.61	15.96	19.64	—	—	14.12	7.59	3.51	0.54	—
St. Pierre & Miquelon														
St. Pierre	46.77 N	56.17 W	4.43	6.61	12.50	17.57	18.55	17.84	19.95	16.46	12.76	8.15	3.69	3.33
Singapore														
Singapore	1.37 N	103.98 E	19.08	20.94	20.75	18.20	14.89	15.22	13.92	16.66	16.51	15.82	13.81	12.67
South Korea														
Seoul	37.57 N	126.97 E	6.24	9.40	10.34	13.98	16.35	17.49	10.65	12.94	11.87	10.35	6.47	5.14
South Africa														
Cape Town	33.98 S	18.60 E	27.47	25.57	—	15.81	11.44	9.08	8.35	13.76	17.30	22.16	26.37	27.68
Port Elizabeth	33.98 S	25.60 E	27.22	22.06	19.01	15.29	11.79	11.13	10.73	13.97	18.52	23.09	23.15	27.26
Pretoria	25.73 S	28.18 E	26.06	22.43	20.52	16.09	15.67	13.67	15.19	18.65	21.62	21.75	24.82	23.43
Spain														
Madrid	40.45 N	3.72 W	7.73	10.53	15.35	21.74	22.81	22.05	26.27	22.90	18.89	10.21	8.69	5.56
Sudan														
Wad Madani	14.40 N	33.48 E	21.92	24.01	23.43	25.17	23.92	23.51	22.40	22.85	21.75	20.47	20.19	19.21
Elfasher	13.62 N	25.33 E	21.56	21.84	24.54	25.29	24.31	24.15	22.87	21.19	22.58	23.85	—	—
Shambat	15.67 N	32.53 E	23.90	27.38	—	27.45	23.21	26.15	23.55	25.46	24.05	23.51	23.82	22.53
Sweden														
Karlstad	59.37 N	13.47 E	1.26	3.13	5.02	14.01	19.90	16.70	20.92	14.14	10.52	3.98	1.47	0.94
Lund	55.72 N	13.22 E	1.97	3.47	6.66	12.48	17.83	13.38	18.74	14.99	10.39	5.45	1.82	1.21
Stockholm	59.35 N	18.07 E	1.32	2.69	4.75	13.21	15.58	14.79	20.52	14.48	10.50	4.04	1.19	0.83

(continued)

TABLE A2.3a ***(Continued)***

Position	Lat	Long	January	February	March	April	May	June	July	August	September	October	November	December
Switzerland														
Geneva	46.25 N	6.13 E	2.56	7.21	9.46	17.07	20.98	19.78	22.38	20.50	13.62	8.44	3.31	2.87
Zurich	47.48 N	8.53 E	2.31	7.02	7.54	15.04	16.33	16.73	20.28	18.32	12.52	7.18	2.64	2.29
Thailand														
Bangkok	13.73 N	100.57 E	16.67	19.34	23.00	22.48	20.59	17.71	18.02	16.04	16.23	16.81	18.60	16.43
Trinidad & Tobago														
Crown Point	11.15 N	60.83 W	13.05	15.61	15.17	16.96	17.61	15.37	13.16	13.08	12.24	8.76	—	—
Tunisia														
Sidi Bouzid	36.87 N	10.35 E	7.88	10.38	13.20	17.98	25.12	26.68	27.43	24.33	18.87	12.11	9.37	6.72
Tunis	36.83 N	10.23 E	7.64	9.88	14.79	31.61	25.31	26.03	26.60	20.37	19.58	12.91	9.35	7.16
Ukraine														
Kiev	50.40 N	30.45 E	2.17	4.87	11.15	12.30	20.49	—	18.99	18.55	9.72	9.84	3.72	2.52
Uzbekistan														
Tashkent	41.27 N	69.27 E	7.27	10.81	15.93	23.60	25.21	29.53	28.50	26.68	20.76	13.25	8.61	4.59
Venezuela														
Caracas	10.50 N	66.88 W	14.25	13.56	16.30	15.56	15.69	15.56	16.28	17.11	17.04	15.14	14.74	13.50
St. Antonio	7.85 N	72.45 W	11.78	10.54	10.65	12.07	12.65	21.20	14.68	15.86	16.62	15.32	12.28	11.28
St. Fernando	7.90 N	67.42 W	14.92	16.82	16.89	—	—	14.09	13.78	14.42	14.86	15.27	14.25	13.11
Vietnam														
Hanoi	21.03 N	105.85 E	5.99	7.48	8.73	13.58	19.10	21.26	19.85	19.78	20.67	14.78	12.44	13.21
Yogoslavia														
Beograd	44.78 N	20.53 E	4.92	6.27	10.64	14.74	20.95	22.80	22.09	20.27	15.57	11.24	6.77	4.99
Kopaonik	43.28 N	20.80 E	7.03	10.93	14.75	12.78	13.54	20.43	22.48	—	20.14	11.61	6.26	4.64
Portoroz	45.52 N	13.57 E	5.11	7.84	13.75	17.30	23.66	22.31	25.14	21.34	13.40	8.98	6.04	3.92
Zambia														
Lusaka	15.42 S	28.32 W	16.10	18.02	20.24	19.84	17.11	16.37	19.45	20.72	21.68	23.83	23.85	20.52
Zimbabwe														
Bulawayo	20.15 S	28.62 N	20.03	22.11	21.03	18.09	17.15	15.36	16.46	19.49	21.55	23.44	25.08	23.46
Harare	17.83 S	31.02 N	19.38	19.00	19.22	17.67	18.35	16.10	14.55	17.87	21.47	23.98	19.92	21.88

Note: Data for 872 locations is available from these sources in 68 countries.

[a] Source for Canadian Data: Environment Canada: Internet address: http://www.ec.gc.ca./envhome.html

Source: From Voeikov Main Geophysical Observatory, Russia: Internee address: http://wrdc-mgo.nrel.gov/html/get_data-ap.html

TABLE A2.3b Average Daily Solar Radiation on a Horizontal Surface in U.S.A. (Units: MJ/sq. m-day)

Position	January	February	March	April	May	June	July	August	September	October	November	December	Average
Alabama													
Birmingham	9.20	11.92	15.67	19.65	21.58	22.37	21.24	20.21	17.15	14.42	10.22	8.40	16.01
Montgomery	9.54	12.49	16.24	20.33	22.37	23.17	21.80	20.56	17.72	14.99	10.90	8.97	16.58
Alaska													
Fairbanks	0.62	2.77	8.31	14.66	17.98	19.65	16.92	12.36	7.02	3.20	1.01	0.23	8.74
Anchorage	1.02	3.41	8.18	13.06	15.90	17.72	16.69	12.72	8.06	3.97	1.48	0.56	8.63
Nome	0.51	2.95	8.29	15.22	18.97	19.65	16.69	11.81	7.72	3.63	0.99	0.09	8.86
St. Paul Island	1.82	4.32	8.52	12.72	14.08	14.42	12.83	10.33	7.84	4.54	2.16	1.25	7.95
Yakutat	1.36	3.63	7.72	12.61	14.76	15.79	14.99	12.15	7.95	3.97	1.82	0.86	8.18
Arizona													
Phoenix	11.58	15.33	19.87	25.44	28.85	30.09	27.37	25.44	21.92	17.60	12.95	10.56	20.56
Tucson	12.38	15.90	20.21	25.44	28.39	29.30	25.44	24.08	21.58	17.94	13.63	11.24	20.44
Arkansas													
Little Rock	9.09	11.81	15.56	19.19	21.80	23.51	23.17	21.35	17.26	14.08	9.77	8.06	16.24
Fort Smith	9.31	12.15	15.67	19.31	21.69	23.39	23.85	24.46	17.26	13.97	9.88	8.29	16.35
California													
Bakersfield	8.29	11.92	16.69	22.15	26.57	28.96	28.73	26.01	21.35	15.90	10.33	7.61	18.74
Fresno	7.61	11.58	16.81	22.49	27.14	29.07	28.96	25.89	21.12	15.56	9.65	6.70	18.62
Long Beach	9.99	12.95	17.03	21.60	23.17	24.19	26.12	24.08	19.31	14.99	11.24	9.31	17.83
Sacramento	6.93	10.68	15.56	21.24	25.89	28.28	28.62	25.32	20.56	14.54	8.63	6.25	17.72
San Diego	11.02	13.97	17.72	21.92	22.49	23.28	24.98	23.51	19.53	15.79	12.26	10.22	18.06
San Francisco	7.72	10.68	15.22	20.44	24.08	25.78	26.46	23.39	19.31	13.97	8.97	7.04	16.92
Los Angeles	10.11	13.06	17.26	21.80	23.05	23.74	25.67	23.51	18.97	14.99	11.36	9.31	17.72
Santa Maria	10.22	13.29	17.49	22.26	25.10	26.57	26.91	24.42	20.10	15.67	11.47	9.54	18.62
Colorado													
Boulder	7.84	10.45	15.64	17.94	17.94	20.47	20.28	17.12	16.07	12.09	8.66	7.10	14.31
Colorado Springs	9.09	12.15	16.13	20.33	22.26	24.98	23.96	21.69	18.51	14.42	9.99	8.18	16.81
Connecticut													
Hartford	6.70	9.65	13.17	16.69	19.53	21.24	21.12	18.51	14.76	10.68	6.59	5.45	13.74
Delaware													
Wilmington	7.27	10.22	13.97	17.60	20.33	22.49	21.80	19.65	15.79	11.81	7.84	6.25	14.65
Florida													
Daytona Beach	11.24	13.85	17.94	22.15	23.17	22.03	21.69	20.44	17.72	14.99	12.15	10.33	17.38

(continued)

TABLE A2.3b ***(Continued)***

Position	January	February	March	April	May	June	July	August	September	October	November	December	Average
Jacksonville	10.45	13.17	17.03	21.12	22.03	21.58	21.01	19.42	16.69	14.20	11.47	9.65	16.47
Tallahassee	10.33	13.29	16.92	21.24	22.49	22.03	20.90	19.65	17.72	15.56	11.92	9.77	16.81
Miami	12.72	15.22	18.51	21.58	21.46	20.10	21.10	20.10	17.60	15.67	13.17	11.81	17.38
Key West	13.17	16.01	19.65	22.71	22.83	22.03	22.03	21.01	18.74	16.47	13.85	15.79	18.40
Tampa	11.58	14.42	18.17	22.26	23.05	21.92	20.90	19.65	17.60	16.01	12.83	11.02	17.49
Georgia													
Athens	9.43	12.38	16.01	20.21	22.03	22.83	21.80	20.21	17.26	14.42	10.45	8.40	16.29
Atlanta	9.31	12.26	16.13	20.33	22.37	23.17	22.15	20.56	17.49	14.54	10.56	8.52	16.43
Columbus	9.77	12.72	16.47	20.67	22.37	22.83	21.58	20.33	17.60	14.99	11.02	9.09	16.62
Macon	9.54	12.61	16.35	20.56	22.37	22.83	21.58	20.21	17.26	14.88	10.90	8.86	16.50
Savanna	9.99	12.72	16.81	21.01	22.37	22.60	21.80	19.76	16.92	14.65	11.13	9.20	16.58
Hawaii													
Honolulu	14.08	16.92	19.42	21.24	22.83	23.51	23.74	23.28	21.35	18.06	14.88	13.40	19.42
Idaho													
Boise	5.79	8.97	13.63	18.97	23.51	26.01	27.37	23.62	18.40	12.26	6.70	5.11	15.90
Illinois													
Chicago	6.47	9.31	12.49	16.47	20.44	22.60	22.03	19.31	15.10	10.79	6.47	5.22	13.85
Rockford	6.70	9.77	12.72	16.58	20.33	22.49	22.15	19.42	15.22	10.79	6.59	5.34	14.08
Springfield	7.50	10.33	13.40	17.83	21.46	23.51	23.05	20.56	16.58	12.26	7.72	6.13	15.10
Indiana													
Indianapolis	7.04	9.99	13.17	17.49	21.24	23.28	22.60	20.33	16.35	11.92	7.38	5.79	14.76
Iowa													
Mason City	6.70	9.77	13.29	16.92	20.78	22.83	22.71	19.76	15.33	10.90	6.59	5.45	14.31
Waterloo	6.81	9.77	13.06	16.92	20.56	22.83	22.60	19.76	15.33	10.90	6.70	5.45	14.20
Kansas													
Dodge City	9.65	12.83	16.69	21.01	23.28	25.78	25.67	22.60	18.40	14.42	10.11	8.40	17.49
Goodland	8.97	11.92	16.13	20.44	22.71	25.78	25.55	22.60	18.28	14.08	9.65	7.84	17.03
Kentucky													
Lexington	7.27	9.88	13.51	17.60	20.56	22.26	21.46	19.65	16.01	12.38	7.95	6.25	14.54
Louisville	7.27	10.22	13.63	17.83	20.90	22.71	22.03	20.10	16.35	12.38	7.95	6.25	14.76
Louisiana													
New Orleans	9.77	12.83	16.01	19.87	21.80	22.03	20.67	19.65	17.60	15.56	11.24	9.31	16.35
Lake Charles	9.77	12.83	16.13	19.31	21.58	22.71	21.58	20.33	18.06	15.56	11.47	9.31	16.58
Maine													
Portland	6.70	9.99	13.78	16.92	19.99	21.92	21.69	19.31	15.22	10.56	6.47	5.45	13.97
Maryland													

Baltimore	7.38	10.33	13.97	17.60	20.21	22.15	21.69	19.19	15.79	11.92	8.06	6.36	14.54
Massachusetts													
Boston	6.70	9.65	13.40	16.92	20.21	22.03	21.80	19.31	15.33	10.79	6.81	5.45	14.08
Michigan													
Detroit	5.91	8.86	12.38	16.47	20.33	22.37	21.92	18.97	14.76	10.11	6.13	4.66	13.63
Lansing	5.91	8.86	12.49	16.58	20.21	22.26	21.92	18.85	14.54	9.77	5.91	4.66	13.51
Minnesota													
Duluth	5.68	9.31	13.74	17.38	20.10	21.46	21.80	18.28	13.29	8.86	5.34	4.43	13.29
Minneapolis	6.36	9.77	13.51	16.92	20.56	22.49	22.83	19.42	14.65	9.99	6.13	4.88	13.97
Rochester	6.36	9.65	13.17	16.58	20.10	22.15	22.15	19.08	14.54	10.11	6.25	5.11	13.74
Mississippi													
Jackson	9.43	12.38	16.13	19.87	22.15	23.05	22.15	19.08	14.54	10.11	6.25	5.11	13.74
Missouri													
Columbia	8.06	10.90	14.31	18.62	21.58	23.62	23.85	21.12	16.69	12.72	8.29	6.70	15.56
Kansas City	7.95	10.68	14.08	18.28	21.24	23.28	23.62	20.78	16.58	12.72	8.40	6.70	15.44
Springfield	8.52	11.02	14.65	18.62	21.24	23.05	23.62	21.24	16.81	13.17	8.86	7.27	15.67
St. Louis	7.84	10.56	13.97	18.06	21.12	23.05	22.94	20.44	16.58	12.49	8.18	6.59	15.22
Montana													
Helena	5.22	8.29	12.61	17.15	20.67	23.28	25.21	21.24	15.79	10.45	6.02	4.43	14.20
Lewistown	5.22	8.40	12.72	17.15	20.33	23.05	24.53	20.78	15.10	10.22	5.91	4.32	13.97
Nebraska													
Omaha	7.50	10.33	13.97	18.06	21.24	2.40	23.51	20.56	16.01	11.81	7.61	6.13	15.10
Lincoln	7.33	10.10	13.65	16.22	19.26	21.21	22.15	18.87	15.44	11.54	7.76	6.20	14.16
Nevada													
Elko	7.61	10.56	14.42	18.85	22.71	25.67	26.69	23.62	19.31	13.63	8.29	6.70	16.58
Las Vegas	10.79	14.42	19.42	24.87	28.16	30.09	28.28	25.89	22.15	17.03	12.15	9.88	20.33
Reno	8.29	11.58	16.24	21.24	25.10	27.48	28.16	24.98	20.56	14.88	9.31	7.38	17.94
New Hampshire													
Concord	6.81	10.11	13.97	16.92	20.21	21.80	21.80	19.08	14.99	10.45	6.47	5.45	14.08
New Jersey													
Atlantic City	7.38	10.22	13.97	17.49	20.21	21.92	21.24	19.19	15.79	11.92	8.06	6.36	14.54
Newark	6.93	9.77	13.51	17.26	19.76	21.35	21.01	18.85	15.33	11.36	7.27	5.68	13.97
New Mexico													
Albuquerque	11.47	14.99	19.31	24.53	27.60	29.07	27.03	24.76	21.12	17.03	12.49	10.33	19.99
New York													
Albany	6.36	9.43	12.95	16.69	19.53	21.46	21.58	18.51	14.65	10.11	6.13	5.00	13.51
Buffalo	5.68	8.40	12.15	16.35	19.76	22.03	21.69	18.62	14.08	9.54	5.68	4.54	13.29
New York City	6.93	9.88	13.85	17.72	20.44	22.03	21.69	19.42	15.56	11.47	7.27	5.79	14.31

(continued)

TABLE A2.3b ***(Continued)***

Position	January	February	March	April	May	June	July	August	September	October	November	December	Average
Rochester	5.68	8.52	12.26	16.58	19.87	21.92	21.69	18.51	14.20	9.54	5.68	4.54	13.29
North Carolina													
Charlotte	8.97	11.81	15.67	19.76	21.58	22.60	21.92	19.99	16.92	13.97	9.99	8.06	16.01
Wilmington	9.31	12.15	16.24	20.44	21.92	22.60	21.58	19.53	16.69	14.08	10.56	8.52	16.13
North Dakota													
Fargo	5.79	9.09	13.17	16.92	20.56	22.37	23.17	19.87	14.31	9.54	5.68	4.54	13.74
Bismarck	6.12	9.75	13.88	17.43	21.45	23.01	24.06	20.12	15.21	10.61	6.28	4.84	14.39
Ohio													
Cleveland	5.79	8.63	12.04	16.58	20.10	22.15	21.92	18.97	14.76	10.22	6.02	4.66	13.51
Columbus	6.47	9.09	12.49	16.58	19.76	21.58	21.12	18.97	15.44	11.24	6.81	5.34	13.74
Dayton	6.81	9.43	12.83	17.03	20.33	22.37	22.37	19.65	15.90	11.47	7.04	5.45	14.20
Youngstown	5.79	8.40	11.92	15.90	19.19	21.24	20.78	18.06	14.31	10.11	6.02	4.77	13.06
Oklahoma													
Oklahoma City	9.88	1.25	16.47	20.33	22.26	24.42	24.98	22.49	18.17	14.54	10.45	8.74	17.15
Oregon													
Eugene	4.54	7.04	11.24	15.79	19.99	22.37	24.19	21.01	15.90	9.65	5.11	3.75	13.40
Medford	5.34	8.52	13.17	18.62	23.39	26.23	27.82	23.96	18.62	11.92	6.02	4.43	15.67
Portland	4.20	6.70	10.68	15.10	18.97	21.24	22.60	19.53	14.88	9.20	4.88	3.52	12.61
Pacific Islands													
Guam	16.35	17.38	19.65	20.78	20.56	19.76	18.28	17.49	17.49	16.58	15.79	15.10	17.94
Pennsylvania													
Philadelphia	7.04	9.88	13.63	17.26	19.99	22.03	21.46	19.42	15.67	11.58	7.72	6.02	14.31
Pittsburgh	6.25	8.97	12.61	16.47	19.65	21.80	21.35	18.85	15.10	10.90	6.59	5.00	13.63
Rhode Island													
Providence	6.70	9.65	13.40	16.92	19.99	21.58	21.24	18.85	15.22	11.02	6.93	5.56	13.97
South Carolina													
Charleston	9.77	12.72	16.81	21.12	22.37	22.37	21.92	19.65	16.92	14.54	11.02	9.09	16.58
Greenville	9.20	12.04	15.90	19.99	21.58	22.60	21.58	19.87	16.81	14.08	10.22	8.18	16.01
South Dakota													
Pierre	6.47	9.54	13.85	17.94	21.46	24.08	24.42	21.46	16.35	11.24	7.04	5.45	14.99
Rapid City	6.70	9.88	14.20	18.28	21.46	24.19	24.42	21.80	16.92	11.81	7.50	5.79	15.33
Tennessee													
Memphis	8.86	11.58	15.22	19.42	22.03	23.85	23.39	21.46	17.38	14.20	9.65	7.84	16.24
Nashville	8.29	11.13	14.65	19.31	21.69	23.51	22.49	20.56	16.81	13.51	8.97	7.15	15.67
Texas													
Austin	10.68	13.63	17.03	19.53	21.24	23.74	24.42	22.83	18.85	15.67	11.92	9.99	17.49

Brownsville	10.33	13.17	16.47	19.08	20.78	22.83	23.28	21.58	18.62	16.13	12.38	9.88	17.03
El Paso	12.38	16.24	20.90	25.44	28.05	28.85	26.46	24.30	21.12	17.72	13.63	11.47	20.56
Houston	9.54	12.26	15.22	18.06	20.21	21.69	21.35	20.21	17.49	15.10	11.02	8.97	15.90
San Antonio	10.88	13.53	16.26	17.35	21.10	23.87	24.92	22.81	19.22	15.52	11.50	9.98	17.24
Utah													
Salt Lake City	6.93	10.45	14.76	19.42	23.39	26.46	26.35	23.39	18.85	13.29	8.06	6.02	16.47
Vermont													
Burlington	5.79	9.20	13.06	16.47	19.87	21.69	21.80	18.74	14.42	9.43	5.56	4.43	13.40
Virginia													
Norfolk	8.06	10.90	14.65	18.51	20.78	22.15	21.12	19.42	16.13	12.49	9.09	7.27	15.10
Richmond	8.06	10.90	14.76	18.62	20.90	22.49	21.58	19.53	16.24	12.61	8.97	7.15	15.22
Washington													
Olympia	3.63	6.02	9.99	14.20	18.06	20.10	21.12	18.17	13.63	7.95	4.32	3.07	11.70
Seattle	3.52	5.91	10.11	14.65	19.08	20.78	21.80	18.51	13.51	7.95	4.20	2.84	11.92
Yakima	4.88	7.95	12.83	17.83	22.49	24.87	25.89	22.26	16.92	10.68	5.56	4.09	17.76
West Virginia													
Charleston	7.04	9.65	13.40	17.15	20.21	21.69	20.90	18.97	15.56	11.81	7.72	6.02	14.20
Elkins	6.93	9.43	12.83	16.35	19.08	20.56	19.99	18.06	14.88	11.13	7.27	5.79	13.51
Wisconsin													
Green Bay	6.25	9.31	13.17	16.81	20.56	22.49	22.03	18.85	14.20	9.65	5.79	4.88	13.74
Madison	6.59	9.88	13.29	16.92	20.67	22.83	22.37	19.42	14.76	3.41	6.25	5.22	14.08
Milwaukee	6.47	9.31	12.72	16.69	20.78	22.94	22.60	19.42	14.88	10.22	6.25	5.11	13.97
Wyoming													
Rock Springs	7.61	10.90	15.10	19.42	23.17	26.01	25.78	22.94	18.62	13.40	8.40	6.70	16.58
Sendan	6.47	9.77	13.97	17.94	20.90	23.85	24.64	21.69	16.47	11.24	7.15	5.56	14.99

Source: From National Renewable Energy Laboratory, U.S.A.; Internet Address: http://rredc.nrel.gov/solar.

TABLE A2.4 Reflectivity Values for Characteristic Surfaces (Integrated Over Solar Spectrum and Angle of Incidence)

Surface	Average Reflectivity
Snow (freshly fallen or with ice film)	0.75
Water surfaces (relatively large incidence angles)	0.07
Soils (clay, loam, etc.)	0.14
Earth roads	0.04
Coniferous forest (winter)	0.07
Forests in autumn, ripe field crops, plants	0.26
Weathered blacktop	0.10
Weathered concrete	0.22
Dead leaves	0.30
Dry grass	0.20
Green grass	0.26
Bituminous and gravel roof	0.13
Crushed rock surface	0.20
Building surfaces, dark (red brick, dark paints, etc.)	0.27
Building surfaces, light (light brick, light paints, etc.)	0.60

Source: From Hunn, B. D. and Calafell, D. O. 1977. *Solar Energy,* Vol. 19, p. 87; see also List, R. J. 1949. *Smithsonian Meteorological Tables*, 6th Ed., pp. 442–443. Smithsonian Institution Press.

A3

Properties of Gases, Vapors, Liquids and Solids

Nitin Goel

Intel Technology India Pvt. Ltd.

TABLE A3.1 Properties of Dry Air at Atmospheric Pressures between 250 and 1000 K

T^a (K)	ρ (kg/m^3)	c_p (kJ/kg K)	μ (kg/m s$\times10^5$)	ν (m^2/s$\times10^6$)	k (W/m K)	α (m^2/s$\times10^4$)	dPr
250	1.4128	1.0053	1.488	9.49	0.02227	0.13161	0.722
300	1.1774	1.0057	1.983	15.68	0.02624	0.22160	0.708
350	0.9980	1.0090	2.075	20.76	0.03003	0.2983	0.697
400	0.8826	1.0140	2.286	25.90	0.03365	0.3760	0.689
450	0.7833	1.0207	2.484	28.86	0.03707	0.4222	0.683
500	0.7048	1.0295	2.671	37.90	0.04038	0.5564	0.680
550	0.6423	1.0392	2.848	44.34	0.04360	0.6532	0.680
600	0.5879	1.0551	3.018	51.34	0.04659	0.7512	0.680
650	0.5430	1.0635	3.177	58.51	0.04953	0.8578	0.682
700	0.5030	1.0752	3.332	66.25	0.05230	0.9672	0.684
750	0.4709	1.0856	3.481	73.91	0.05509	1.0774	0.686
800	0.4405	1.0978	3.625	82.29	0.05779	1.1951	0.689
850	0.4149	1.1095	3.765	90.75	0.06028	1.3097	0.692
900	0.3925	1.1212	3.899	99.3	0.06279	1.4271	0.696
950	0.3716	1.1321	4.023	108.2	0.06525	1.5510	0.699
1000	0.3524	1.1417	4.152	117.8	0.06752	1.6779	0.702

[a] Symbols: K = absolute temperature, degrees Kelvin; $\nu=\mu/\rho$; ρ = density; c_p specific heat capacity; $\alpha=c_p\rho/k$; μ = viscosity; k = thermal conductivity; Pr = Prandtl number, dimensionless. The values of μ, k, c_p, and Pr are not strongly pressure-dependent and may be used over a fairly wide range of pressures.

Source: From Natl. Bureau Standards (U.S.) Circ. 564, 1955.

TABLE A3.2 Properties of Water (Saturated Liquid) between 273 and 533 K

T			c_p (kJ/kg °C)	ρ (kg/m^3)	μ (kg/m s)	k (W/m °C)	Pr	$(g\beta\rho^2 c_p/\mu k)(m^{-3}{}^\circ\mathrm{C}^{-1})$
K	°F	°C						
273	32	0	4.225	999.8	1.79×10^{-3}	0.566	13.25	
277.4	40	4.44	4.208	999.8	1.55	0.575	11.35	1.91×10^{9}
283	50	10	4.195	999.2	1.31	0.585	9.40	6.34×10^{9}
288.6	60	15.56	4.186	998.6	1.12	0.595	7.88	1.08×10^{10}
294.1	70	21.11	4.179	997.4	9.8×10^{-4}	0.604	6.78	1.46×10^{10}
299.7	80	26.67	4.179	995.8	8.6	0.614	5.85	1.91×10^{10}
302.2	90	32.22	4.174	994.9	7.65	0.623	5.12	2.48×10^{10}
310.8	100	37.78	4.174	993.0	6.82	0.630	4.53	3.3×10^{10}
316.3	110	43.33	4.174	990.6	6.16	0.637	4.04	4.19×10^{10}
322.9	120	48.89	4.174	988.8	5.62	0.644	3.64	4.89×10^{10}
327.4	130	54.44	4.179	985.7	5.13	0.649	3.30	5.66×10^{10}
333.0	140	60	4.179	983.3	4.71	0.654	3.01	6.48×10^{10}
338.6	150	65.55	4.183	980.3	4.3	0.659	2.73	7.62×10^{10}
342.1	160	71.11	4.186	977.3	4.01	0.665	2.53	8.84×10^{10}
349.7	170	76.67	4.191	973.7	3.72	0.668	2.33	9.85×10^{10}
355.2	180	82.22	4.195	970.2	3.47	0.673	2.16	1.09×10^{11}
360.8	190	87.78	4.199	966.7	3.27	0.675	2.03	
366.3	200	93.33	4.204	963.2	3.06	0.678	1.90	
377.4	220	104.4	4.216	955.1	2.67	0.684	1.66	
388.6	240	115.6	4.229	946.7	2.44	0.685	1.51	
399.7	260	126.7	4.250	937.2	2.19	0.685	1.36	
410.8	280	137.8	4.271	928.1	1.98	0.685	1.24	
421.9	300	148.9	4.296	918.0	1.86	0.684	1.17	
449.7	350	176.7	4.371	890.4	1.57	0.677	1.02	
477.4	400	204.4	4.467	859.4	1.36	0.665	1.00	
505.2	450	232.2	4.585	825.7	1.20	0.646	0.85	
533.0	500	260	4.731	785.2	1.07	0.616	0.83	

Source: Adapted from Brown, A. I. and S. M. Marco. 1958. Introduction to Heat Transfer, 3d Ed., McGraw-Hill Book Company, New York.

TABLE A3.3 Emittances and Absorptances of Materials

Substance	Short-Wave Absorptance	Long-Wave Emittance	$a\ \varepsilon$
Class I substances: Absorptance to emittance ratios less than 0.5			
Magnesium carbonate, $MgCO_3$	0.025–0.04	0.79	0.03–0.05
White plaster	0.07	0.91	0.08
Snow, fine particles, fresh	0.13	0.82	0.16
White paint, 0.017 in. on aluminum	0.20	0.91	0.22
Whitewash on galvanized iron	0.22	0.90	0.24
White paper	0.25–0.28	0.95	0.26–0.29
White enamel on iron	0.25–0.45	0.9	0.28–0.5
Ice, with sparse snow cover	0.31	0.96–0.97	0.32
Snow, ice granules	0.33	0.89	0.37
Aluminum oil base paint	0.45	0.90	0.50
White powdered sand	0.45	0.84	0.54
Class II substances: Absorptance to emittance ratios between 0.5 and 0.9			
Asbestos felt	0.25	0.50	0.50
Green oil base paint	0.5	0.9	0.56
Bricks, red	0.55	0.92	0.60
Asbestos cement board, white	0.59	0.96	0.61
Marble, polished	0.5–0.6	0.9	0.61
Wood, planed oak	–	0.9	–
Rough concrete	0.60	0.97	0.62
Concrete	0.60	0.88	0.68
Grass, green, after rain	0.67	0.98	0.68
Grass, high and dry	0.67–0.69	0.9	0.76
Vegetable fields and shrubs, wilted	0.70	0.9	0.78
Oak leaves	0.71–0.78	0.91–0.95	0.78–0.82
Frozen soil	–	0.93–0.94	–
Desert surface	0.75	0.9	0.83
Common vegetable fields and shrubs	0.72–0.76	0.9	0.82
Ground, dry plowed	0.75–0.80	0.9	0.83–0.89
Oak woodland	0.82	0.9	0.91
Pine forest	0.86	0.9	0.96
Earth surface as a whole (land and sea, no clouds)	0.83	10^{10}	–
Class III substances: Absorptance to emittance ratios between 0.8 and 1.0			
Grey paint	0.75	0.95	0.79
Red oil base paint	0.74	0.90	0.82
Asbestos, slate	0.81	0.96	0.84
Asbestos, paper		0.93–0.96	
Linoleum, red–brown	0.84	0.92	0.91
Dry sand	0.82	0.90	0.91
Green roll roofing	0.88	0.91–0.97	0.93
Slate, dark grey	0.89	–	
Old grey rubber		0.86	–
Hard black rubber	–	0.90–0.95	
Asphalt pavement	0.93	–	–
Black cupric oxide on copper	0.91	0.96	0.95
Bare moist ground	0.9	0.95	0.95
Wet sand	0.91	0.95	0.96
Water	0.94	0.95–0.96	0.98
Black tar paper	0.93	0.93	1.0
Black gloss paint	0.90	0.90	1.0
Small hole in large box, furnace, or enclosure	0.99	0.99	1.0
"Hohlraum," theoretically perfect black body	1.0	1.0	1.0
Class IV substances: Absorptance to emittance ratios greater than 1.0			
Black silk velvet	0.99	0.97	1.02

(continued)

TABLE A3.3 ***(Continued)***

Substance	Short-Wave Absorptance	Long-Wave Emittance	*a ε*
Alfalfa, dark green	0.97	0.95	1.02
Lampblack	0.98	0.95	1.03
Black paint, 0.017 in. on aluminum	0.94–0.98	0.88	1.07–1.11
Granite	0.55	0.44	1.25
Graphite	0.78	0.41	1.90
High ratios, but absorptances less than 0.80			
Dull brass, copper, lead	0.2–0.4	0.4–0.65	1.63–2.0
Galvanized sheet iron, oxidized	0.8	0.28	2.86
Galvanized iron, clean, new	0.65	0.13	5.0
Aluminum foil	0.15	0.05	3.00
Magnesium	0.3	0.07	4.3
Chromium	0.49	0.08	6.13
Polished zinc	0.46	0.02	23.0
Deposited silver (optical reflector) untarnished	0.07	0.01	
Class V substances: Selective surfaces[a]			
Plated metals:[b]			
Black sulfide on metal	0.92	0.10	9.2
Black cupric oxide on sheet aluminum	0.08–0.93	0.09–0.21	
Copper ($5\times10\sim^{5}$ cm thick) on nickel or silver-plated metal			
Cobalt oxide on platinum			
Cobalt oxide on polished nickel	0.93–0.94	0.24–0.40	3.9
Black nickel oxide on aluminum	0.85–0.93	0.06–0.1	14.5–15.5
Black chrome	0.87	0.09	9.8
Particulate coatings:			
Lampblack on metal			
Black iron oxide, 47 μm grain size, on aluminum			
Geometrically enhanced surfaces:[c]			
Optimally corrugated greys	0.89	0.77	1.2
Optimally corrugated selectives	0.95	0.16	5.9
Stainless-steel wire mesh	0.63–0.86	0.23–0.28	2.7–3.0
Copper, treated with NaClO, and NaOH	0.87	0.13	6.69

[a] Selective surfaces absorb most of the solar radiation between 0.3 and 1.9 μm, and emit very little in the 5–15 μm range–the infrared.

[b] For a discussion of plated selective surfaces, see Daniels, *Direct Use of the Sun's Energy*, especially chapter 12.

[c] For a discussion of how surface selectivity can be enhanced through surface geometry, see K. G. T. Hollands, July 1963. Directional selectivity emittance and absorptance properties of vee corrugated specular surfaces, *J. Sol. Energy Sci. Eng, vol. 3.*

Source: From Anderson, B. 1977. *Solar Energy*, McGraw-Hill Book Company. With permission.

TABLE A3.4 Thermal Properties of Metals and Alloys

Material	*k*, Btu/(hr)(ft.)(°F)				*c*, Btu/(lb$_m$)(°F)	*ρ*, lb$_m$/ft.^{3}	*α*, ft.^{2}/hr
	32°F	212°F	572°F	932°F	32°F	32°F	32°F
Metals							
Aluminum	117	119	133	155	0.208	169	3.33
Bismuth	4.9	3.9	…	…	0.029	612	0.28
Copper, pure	224	218	212	207	0.091	558	4.42
Gold	169	170	…	…	0.030	1,203	4.68
Iron, pure	35.8	36.6	…	…	0.104	491	0.70
Lead	20.1	19	18	…	0.030	705	0.95
Magnesium	91	92	…	…	0.232	109	3.60
Mercury	4.8	…	…	…	0.033	849	0.17
Nickel	34.5	34	32	…	0.103	555	0.60
Silver	242	238	…	…	0.056	655	6.6
Tin	36	34	…	…	0.054	456	1.46
Zinc	65	64	59	…	0.091	446	1.60
Alloys							
Admiralty metal	65	64					
Brass, 70% Cu, 30% Zn	56	60	66	…	0.092	532	1.14
Bronze, 75% Cu, 25% Sn	15	…	…	…	0.082	540	0.34
Cast iron							
Plain	33	31.8	27.7	24.8	0.11	474	0.63
Alloy	30	28.3	27		0.10	455	0.66
Constantan, 60% Cu, 40% Ni	12.4	12.8			0.10	557	0.22
18-8 Stainless steel,							
Type 304	8.0	9.4	10.9	12.4	0.11	488	0.15
Type 347	8.0	9.3	11.0	12.8	0.11	488	0.15
Steel, mild, 1% C	26.5	26	25	22	0.11	490	0.49

Source: From Kreith, F. 1997. *Principles of Heat Transfer*, PWS Publishing Co., Boston.

TABLE A3.5 Thermal Properties of Some Insulating and Building Materials

Material	Average, Temperature, °F	k, Btu/(hr)(ft.)(°F)	c, Btu/(lb_m)(°F)	ρ, $lb_m/ft.^3$	a, $ft.^2/hr$
Insulating Materials					
Asbestos	32	0.087	0.25	36	−0.01
	392	0.12		36	−0.01
Cork	86	0.025	0.04	10	−0.006
Cotton, fabric	200	0.046			
Diatomaceous earth, powdered	100	0.030	0.21	14	−0.01
	300	0.036	…		
	600	0.046	…		
Molded pipe covering	400	0.051	…	26	
	1600	0.088	…		
Glass Wool					
Fine	20	0.022	…		
	100	0.031	…	1.5	
	200	0.043	…		
Packed	20	0.016	…		
	100	0.022	…	6.0	
	200	0.029	…		
Hair felt	100	0.027	…	8.2	
Kaolin insulating brick	932	0.15	…	27	
	2102	0.26	…		
Kaolin insulating firebrick	392	0.05	…	19	
	1400	0.11	…		
85% magnesia	32	0.032	…	17	
	200	0.037	…	17	
Rock wool	20	0.017	…	8	
	200	0.030	…		
Rubber	32	0.087	0.48	75	0.0024
Building Materials					
Brick					
Fire-clay	392	0.58	0.20	144	0.02
	1832	0.95			
Masonry	70	0.38	0.20	106	0.018
Zirconia	392	0.84	…	304	
	1832	1.13	…		
Chrome brick	392	0.82	…	246	
	1832	0.96	…		
Concrete					
Stone	−70	0.54	0.20	144	0.019
10% Moisture	−70	0.70	…	140	−0.025
Glass, window	−70	−0.45	0.2	170	0.013
Limestone, dry	70	0.40	0.22	105	0.017
Sand					
Dry	68	0.20	…	95	
10% H_2O	68	0.60		100	
Soil					
Dry	70	−0.20	0.44	…	−0.01
Wet	70	−1.5	…		−0.03
Wood					
Oak ⊥ to grain	70	0.12	0.57	51	0.0041
∥ to grain	70	0.20	0.57	51	0.0069
Pine ⊥ to grain	70	0.06	0.67	31	0.0029
∥ to grain	70	0.14	0.67	31	0.0067
Ice	32	1.28	0.46	57	0.048

Source: From Kreith, R. 1997. *Principles of Heat Transfer*, PWS Publishing Co.

TABLE A3.6 Saturated Steam and Water–SI Units

Temperature (K)	Pressure (MN/m^2)	Specific Volume (m^3/kg)		Specific Energy Internal (kJ/kg)		Specific Enthalpy (kJ/kg)			Specific Entropy (kJ/kg.K)	
		v_f	v_g	u_f	u_g	h_f	h_{fg}	h_g	s_f	s_g
273.15	0.0006109	0.0010002	206.278	−0.03	2375.3	−0.02	2501.4	2501.3	−0.0001	9.1565
273.16	0.0006113	0.0010002	206.136	0	2375.3	+0.01	2501.3	2501.4	0	9.1562
278.15	0.0008721	0.0010001	147.120	+20.97	2382.3	20.98	2489.6	2510.6	+0.0761	9.0257
280.13	0.0010000	0.0010002	129.208	29.30	2385.0	29.30	2484.9	2514.2	0.1059	8.975
283.15	0.0012276	0.0010004	106.379	42.00	2389.2	42.01	2477.7	2519.8	0.1510	8.9008
286.18	0.0015000	0.0010007	87.980	54.71	2393.3	54.71	2470.6	2525.3	0.1957	8.8279
288.15	0.0017051	0.0010009	77.926	62.99	2396.1	62.99	2465.9	2528.9	0.2245	8.7814
290.65	0.0020000	0.0010013	67.004	73.48	2399.5	73.48	2460.0	2533.5	0.2607	8.7237
293.15	0.002339	0.0010018	57.791	83.95	2402.9	83.96	2454.1	2538.1	0.2966	8.6672
297.23	0.0030000	0.0010027	45.665	101.04	2408.5	101.05	2444.5	2545.5	0.3545	8.5776
298.15	0.003169	0.0010029	43.360	104.88	2409.8	104.89	2442.3	2547.2	0.3674	8.5580
302.11	0.004000	0.0010040	34.800	121.45	2415.2	121.46	2432.9	2554.4	0.4226	8.4746
303.15	0.004246	0.0010043	32.894	125.78	2416.6	125.79	2430.5	2556.3	0.4369	8.4533
306.03	0.005000	0.0010053	28.192	137.81	2420.5	137.82	2423.7	2561.5	0.4764	8.3951
308.15	0.005628	0.0010060	25.216	146.67	2423.4	146.68	2418.6	2565.3	0.5053	8.3531
309.31	0.006000	0.0010064	23.739	151.53	2425.0	151.53	2415.9	2567.4	0.5210	8.3304
312.15	0.007000	0.0010074	20.530	163.39	2428.8	163.40	2409.1	2572.5	0.5592	8.2758
313.15	0.007384	0.0010078	19.523	167.56	2430.1	167.57	2406.7	2574.3	0.5725	8.2570
314.66	0.008000	0.0010084	18.103	173.87	2432.2	173.88	2403.1	2577.0	0.5926	8.2287
316.91	0.009000	0.0010094	16.203	183.27	2435.2	183.29	2397.7	2581.0	0.6224	8.1872
318.15	0.009593	0.0010099	15.258	188.44	2436.8	188.45	2394.8	2583.2	0.6387	8.1648
318.96	0.010000	0.0010102	14.674	191.82	2437.9	191.83	2392.8	2584.7	0.6493	8.1502
323.15	0.012349	0.0010121	12.032	209.32	2443.5	209.33	2382.7	2592.1	0.7038	8.0763
327.12	0.015000	0.0010141	10.022	225.92	2448.7	225.94	2373.1	2599.1	0.7549	8.0085
328.15	0.015758	0.0010146	9.568	230.21	2450.1	230.23	2370.7	2600.9	0.7679	7.9913
333.15	0.019940	0.0010172	7.671	251.11	2456.6	251.13	2358.5	2609.6	0.8312	7.9096
333.21	0.020000	0.0010172	7.649	251.38	2456.7	251.40	2358.3	2609.7	0.8320	7.9085
338.15	0.025030	0.0010199	6.197	272.02	2463.1	272.06	2346.2	2618.3	0.8935	7.8310
342.25	0.030000	0.0010223	5.229	289.20	2468.4	289.23	2336.1	2625.3	0.9439	7.7686
343.15	0.031190	0.0010228	5.042	292.95	2469.6	292.98	2333.8	2626.8	0.9549	7.7553
348.15	0.038580	0.0010259	4.131	313.90	2475.9	313.93	2221.4	2635.3	1.0155	7.6824
349.02	0.040000	0.0010265	3.993	317.53	2477.0	317.58	2319.2	2636.8	1.0259	7.6700
353.15	0.047390	0.0010291	3.407	334.86	2482.2	334.91	2308.8	2643.7	1.0753	7.6122
354.48	0.050000	0.0010300	3.240	340.44	2483.9	340.49	2305.4	2645.9	1.0910	7.5939

358.15	0.057830	0.0010325	2.828	355.84	2488.4	355.90	2296.0	2651.9	1.1343	7.5445
359.09	0.060000	0.0010331	2.732	359.79	2489.6	359.86	2293.6	2653.5	1.1453	7.5320
363.10	0.070000	0.0010360	2.365	376.63	2494.5	376.70	2283.3	2660.0	1.1919	7.4797
363.15	0.070140	0.0010360	2.361	376.85	2494.5	376.92	2283.2	2660.1	1.1925	7.4791
366.65	0.080000	0.0010386	2.087	391.58	2498.8	391.66	2274.1	2665.8	1.2329	7.4346
368.15	0.084550	0.0010397	1.9819	397.88	2500.6	397.96	2270.2	2668.1	1.2500	7.4159

Subscripts: *f* refers to a property of liquid in equilibrium with vapor; *g* refers to a property of vapor in equilibrium with liquid; *fg* refers to a change by evaporation. Table from Bolz, R. E. and G. L. Tuve, eds. 1973. *CRC Handbook of Tables for Applied Engineering Science*, 2nd Ed., Chemical Rubber Co., Cleveland, Ohio.

TABLE A3.7 Superheated Steam–SI Units

Pressure (MN/m^2) (Saturation Temperature)^a		Temperature									
		50°C	100°C	150°C	200°C	300°C	400°C	500°C	700°C	1000°C	1300°C
		323.15 K	373.15 K	423.15 K	473.15 K	573.15 K	673.15 K	773.15 K	973.15 K	1273.15 K	1573.15 K
0.001	*v*	149.093	172.187	195.272	218.352	264.508	310.661	356.814	449.117	587.571	726.025
(6.98°C)	*u*	2445.4	2516.4	2588.4	2661.6	2812.2	2969.0	3132.4	3479.6	4053.0	4683.7
(280.13 K)	*h*	2594.5	2688.6	2783.6	2880.0	3076.8	3279.7	3489.2	3928.7	4640.6	5409.7
	s	9.2423	9.5129	9.7520	9.9671	10.3443	10.6705	10.9605	11.4655	12.1019	12.6438
0.002	*v*	74.524	86.081	97.628	109.170	132.251	155.329	178.405	224.558	293.785	363.012
(17.50°C)	*u*	2445.2	2516.3	2588.3	2661.6	2812.2	2969.0	3132.4	3479.6	4053.0	4683.7
(290.65 K)	*h*	2594.3	2688.4	2793.6	2879.9	3076.7	3279.7	3489.2	3928.7	4640.6	5409.7
	s	8.9219	9.1928	9.4320	9.6471	10.0243	10.3506	10.6406	11.1456	11.7820	12.3239
0.004	*v*	37.240	43.028	48.806	54.580	66.122	77.662	89.201	112.278	146.892	181.506
(28.%°C)	*u*	2444.9	2516.1	2588.2	2661.5	2812.2	2969.0	3132.3	3479.6	4053.0	4683.7
(302.11 K)	*h*	2593.9	2688.2	2783.4	2879.8	3076.7	3279.6	3489.2	3928.7	4640.6	5409.7
	s	8.6009	8.8724	9.1118	9.3271	9.7044	10.0307	10.3207	10.8257	11.4621	12.0040
0.006	*v*	24.812	28.676	32.532	36.383	44.079	51.774	59.467	74.852	97.928	121.004
(36.16°C)	*u*	2444.6	2515.9	2588.1	2661.4	2812.2	2969.0	31323	3479.6	4053.0	4683.7
(309.31 K)	*h*	2593.4	2688.0	2783.3	2879.7	3076.6	3279.6	3489.1	3928.7	4640.6	5409.7
	s	8.4128	8.6847	8.9244	9.1398	9.5172	9.8435	10.1336	10.6386	11.2750	11.8168
0.008	*v*	18.598	21.501	24.395	27.284	33.058	38.829	44.599	56.138	73.446	90.753
(41.51°C)	*u*	2444.2	2515.7	2588.0	2661.4	2812.1	2969.0	3132.3	3479.6	4053.0	4683.7
(314.66 K)	*h*	2593.0	2687.7	2783.1	2879.6	3076.6	3279.6	3489.1	3928.7	4640.6	5409.7
	s	8.2790	8.5514	8.7914	9.0069	9.3844	9.7107	10.0008	10.5058	11.1422	11.6841
0.010	*v*	14.869	17.196	19.512	21.825	26.445	31.063	35.679	44.911	58.757	72.602
(45.81°C)	*u*	2443.9	2515.5	2587.9	2661.3	2812.1	2968.9	3132.3	3479.6	4053.0	4683.7
(318.96 K)	*h*	2592.6	2687.5	2783.0	2879.5	3076.5	3279.6	3489.1	3928.7	4640.6	5409.7
	s	8.1749	8.4479	8.6882	8.9038	9.2813	9.6077	9.8978	10.4028	11.0393	11.5811
0.020	*v*	7.412	8.585	9.748	10.907	13.219	15.529	17.838	22.455	29.378	36.301
(60.06°C)	*u*	2442.2	2514.6	2587.3	2660.9	2811.9	2968.8	3132.2	3479.5	4053.0	4683.7
(333.21 K)	*h*	2590.4	2686.2	2782.3	2879.1	3076.3	3279.4	3489.0	3928.6	4640.6	5409.7
	s	7.8498	8.1255	8.3669	8.5831	8.9611	9.2876	9.5778	10.0829	10.7193	11.2612
0.040	*v*	3.683	4.279	4.866	5.448	6.606	7.763	8.918	11.227	14.689	18.151
(75.87°C)	*u*	2438.8	2512.6	2586.2	2660.2	2811.5	2968.6	3132.1	3479.4	4052.9	4683.6
(349.02 K)	*h*	2586.1	2683.8	2780.8	2878.1	3075.8	3279.1	3488.8	3928.5	4640.5	5409.6
	s	7.5192	7.8003	8.0444	8.2617	8.6406	8.9674	9.2577	9.7629	10.3994	10.9412
0.060	*v*	2.440	2.844	3.238	3.628	4.402	5.174	5.944	7.484	9.792	12.100
(85.94°C)	*u*	2435.3	2510.6	2585.1	2659.5	2811.2	2968.4	3131.9	3479.4	4052.9	4683.6
(359.09 K)	*h*	2581.7	2681.3	2779.4	2877.2	3075.3	3278.8	3488.6	3928.4	4640.4	5409.6
	s	7.3212	7.6079	7.8546	8.0731	8.4528	8.7799	9.0704	9.5757	10.2122	10.7541
0.080	*v*	1.8183	2.127	2.425	2.718	3.300	3.879	4.458	5.613	7.344	9.075
(93.50°C)	*u*	2431.7	2508.7	2583.9	2658.8	2810.8	2968.1	3131.7	3479.3	4052.8	4683.5
(366.65 K)	*h*	2577.2	2678.8	2777.9	2876.2	3074.8	3278.5	3488.3	3928.3	4640.4	5409.5
	s	7.1775	7.4698	7.7191	7.9388	8.3194	8.6468	8.9374	9.4428	10.0794	10.6213
0.100	*v*	1.4450	1.6958	1.9364	2.172	2.639	3.103	3.565	4.490	5.875	7.260

(99.63°C)	*u*	2428.2	2506.7	2582.8	2658.1	2810.4	2967.9	3131.6	3479.2	4052.8	4683.5
(372.78 K)	*h*	2572.7	2676.2	2776.4	2875.3	3074.3	3278.2	3488.1	3928.2	4640.3	5409.5
	s	7.0633	7.3614	7.6134	7.8343	8.2158	8.5435	8.8342	9.3398	9.9764	10.5183
0.200	*v*	0.6969	0.8340	0.9596	1.0803	1.3162	1.5493	1.7814	2.244	2.937	3.630
(120.23°C)	*u*	2409.5	2496.3	2576.9	2654.4	2808.6	2966.7	3130.8	3478.8	4052.5	4683.2
(393.38 K)	*h*	2548.9	2663.1	2768.8	2870.5	3071.8	3276.6	3487.1	3927.6	4640.0	5409.3
	s	6.6844	7.0135	7.2795	7.5066	7.8926	8.2218	8.5133	9.0194	9.6563	10.1982
0.300	*v*	0.4455	0.5461	0.6339	0.7163	0.8753	1.0315	1.1867	1.4957	1.9581	2.4201
(133.55°C)	*u*	2389.1	2485.4	2570.8	2650.7	2806.7	2965.6	3130.0	3478.4	4052.3	4683.0
(406.70 K)	*h*	2522.7	2649.2	2761.0	2865.6	3069.3	3275.0	3486.0	3927.1	4639.7	5409.0
	s	6.4319	6.7965	7.0778	7.3115	7.7022	8.0330	8.3251	8.8319	9.4690	10.0110
0.400	*v*	0.3177	0.4017	0.4708	0.5342	0.6548	0.7726	0.8893	1.1215	1.4685	1.8151
(143.63°C)	*u*	2366.3	2473.8	2564.5	2646.8	2804.8	2964.4	3129.2	3477.9	4052.0	4682.8
(416.78 K)	*h*	2493.4	2634.5	2752.8	2860.5	3066.8	3273.4	3484.9	3926.5	4639.4	5408.8
	s	6.2248	6.6319	6.9299	7.1706	7.5662	7.8985	8.1913	8.6987	9.3360	9.8780
0.500	*v*		0.3146	0.3729	0.4249	0.5226	0.6173	0.7109	0.8969	1.1747	1.4521
(151.86°C)	*u*		2461.5	2557.9	2642.9	2802.9	2963.2	328.4	3477.5	4051.8	4682.5
(425.01 K)	*h*		2618.7	2744.4	2855.4	3064.2	3271.9	3483.9	3925.9	4639.1	5408.6
	s		6.4945	6.8111	7.0592	7.4599	7.7938	8.0873	8.5952	9.2328	9.7749

[a] Symbols: v = specific volume, m^3/kg; u = specific internal energy, U/kg; h = specific enthalpy, kJ/kg; s = specific entropy, kJ/K kg.

Source: From Bolz, R. E. and G. L. Tuve, Eds. 1973. *CRC Handbook of Tables for Applied Engineering Science*, 2nd Ed., Chemical Rubber Co., Cleveland, Ohio.

A4

Thermophysical Properties of Refrigerants

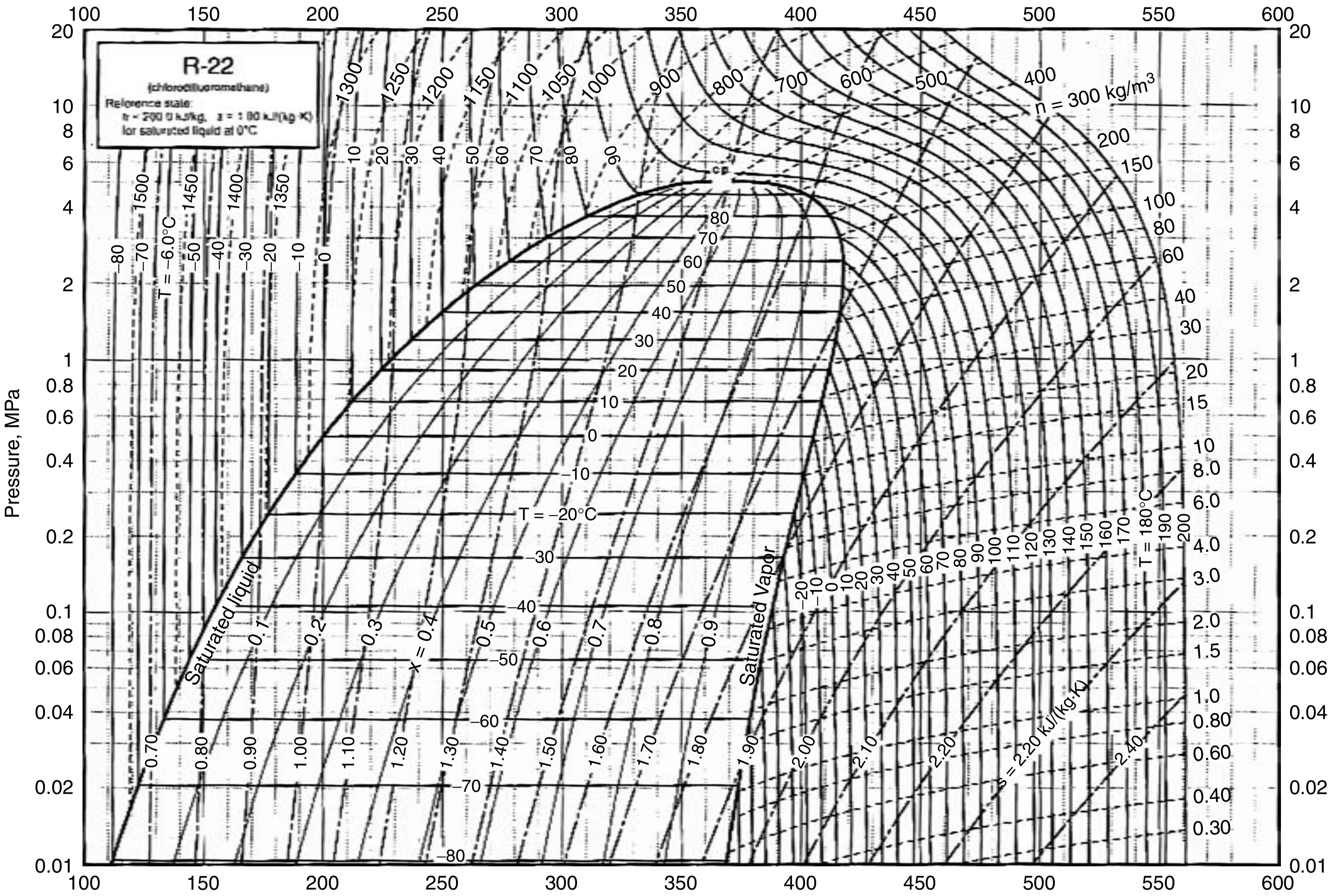
Nitin Goel
Intel Technology India Pvt. Ltd.

R-22 (Chlorodifluoromethane)
R-134a (1,1,12-Tetrafluoroethane)
R-404A [R-125/143a/134a (44/52/4)]
R-407C [R-32/125/134a (23/25/52)
R-410A [R-32/125 (50/50)]
Ammonia/Water
Water/Lithium bromide

The Montreal Protocol, signed in 1987 and later amended in 1990, 1992, 1997, and 1999 controls the production of ozone-depleting substances including refrigerants containing chlorine and/or bromine production chloro-fluoro-carbons (CFC). Pursuent to this treaty, refrigerants such as R-11 and R-12, ceased to exist in 1996 although continued use from existing stocks is permitted. In addition, hydrofluorocarbon (HCFCs) (such as R-22 and R-123) are being phased out, with complete cessation of production by January 1, 2030.

These refrigerants are being replaced by HFC refrigerants which have zero ozone depletion potential. Common HFC refrigerants are R-32, R-125, 134a, and R-143a and their mixtures, such as, R-404A, R-407C, and R-410A.

This appendix gives thermophysical properties of these HFC refrigerants and ammonia water and water–lithium bromide mixtures which are used in absorption refrigeration systems. Properties of R-22 are given to serve as a reference (Figure A4.1 through Figure A4.8).



Properties computed with: NIST REFPROP version 7.0

Based on formulation of Kamei et al. (1995)

FIGURE A4.1 Pressure–enthalpy diagram for refrigerant R-22.

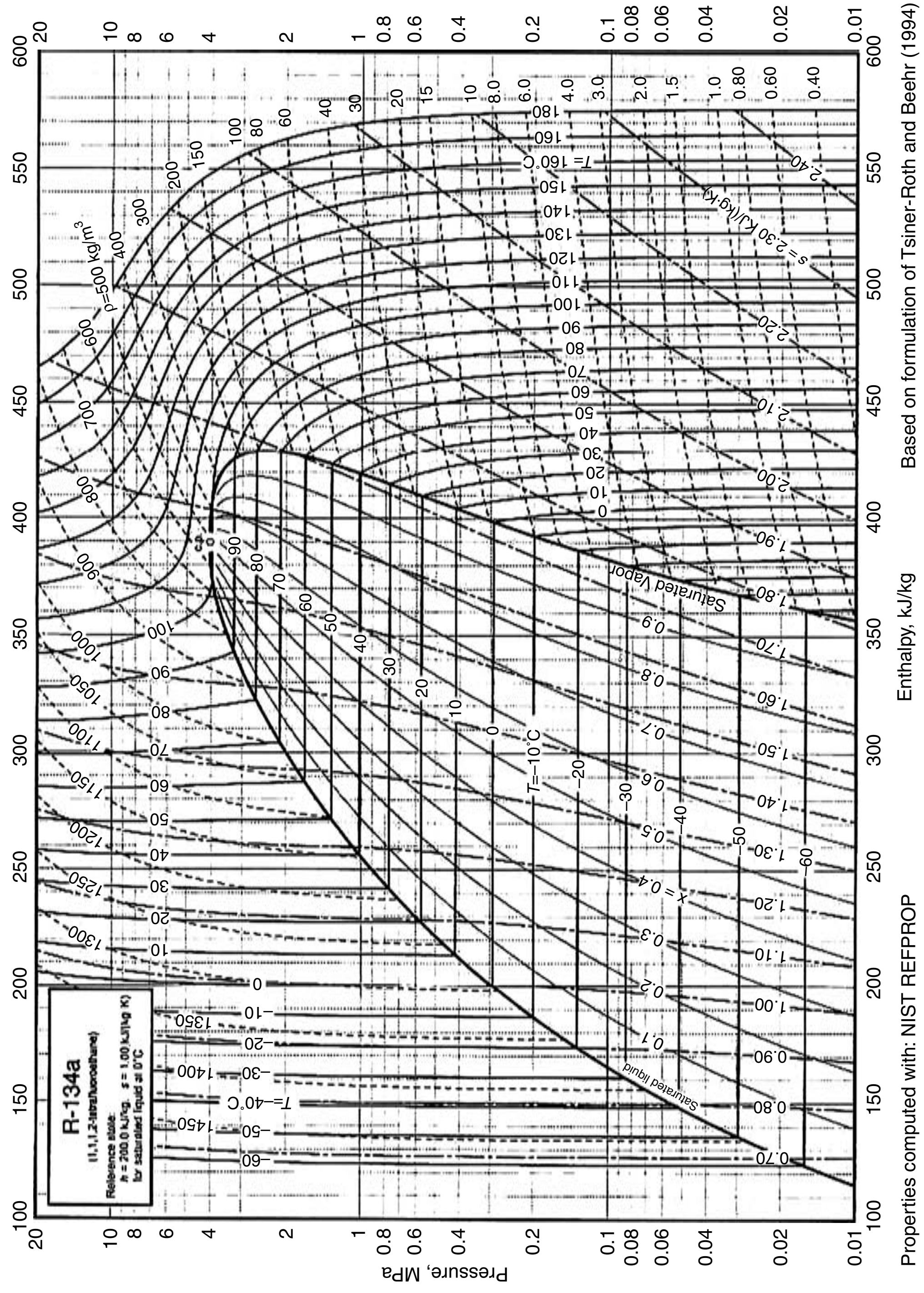


FIGURE A4.2 Pressure–enthalpy diagram for refrigerant R-134a.

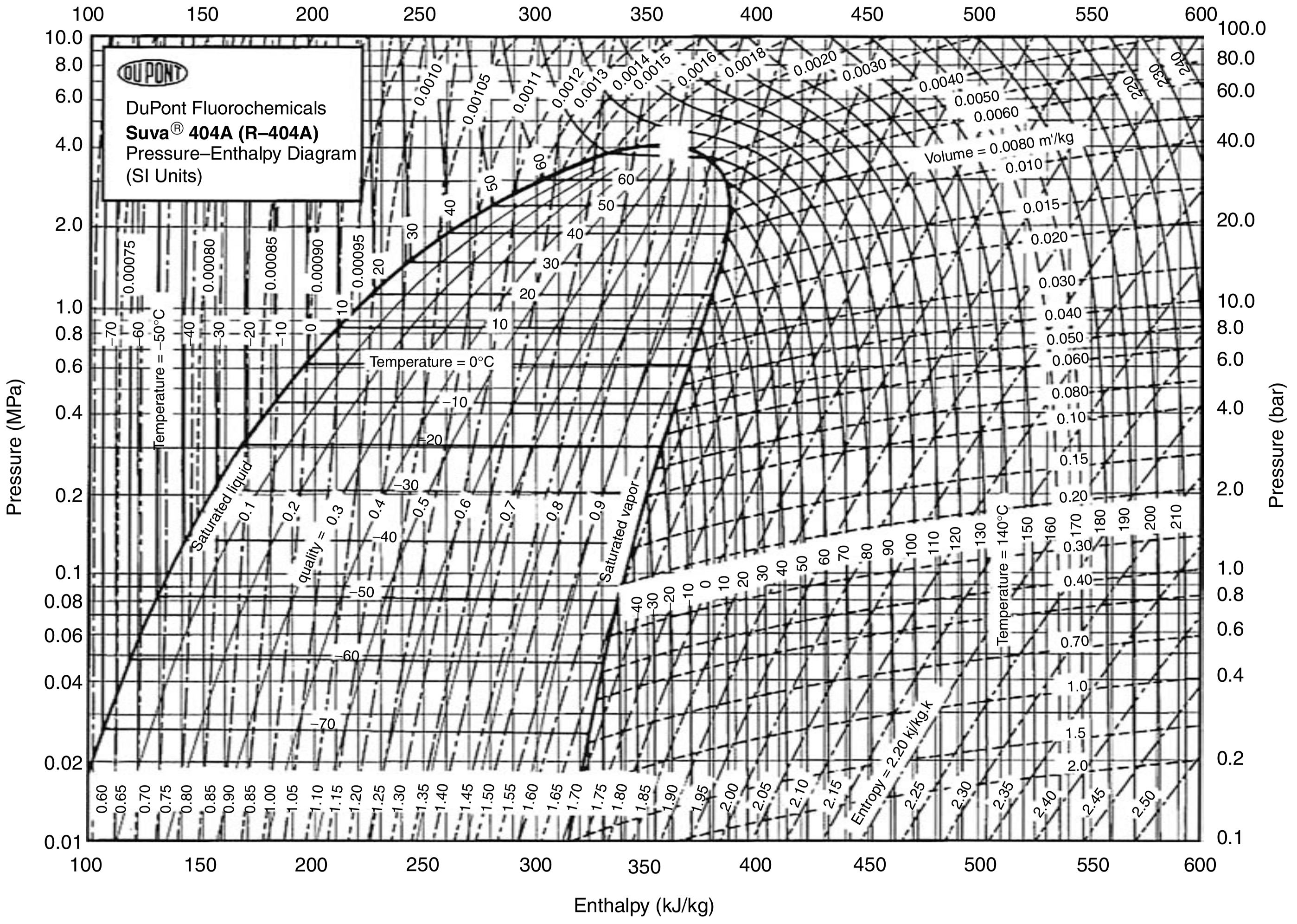


FIGURE A4.3 Pressure–enthalpy diagram for refrigerant R-404A.

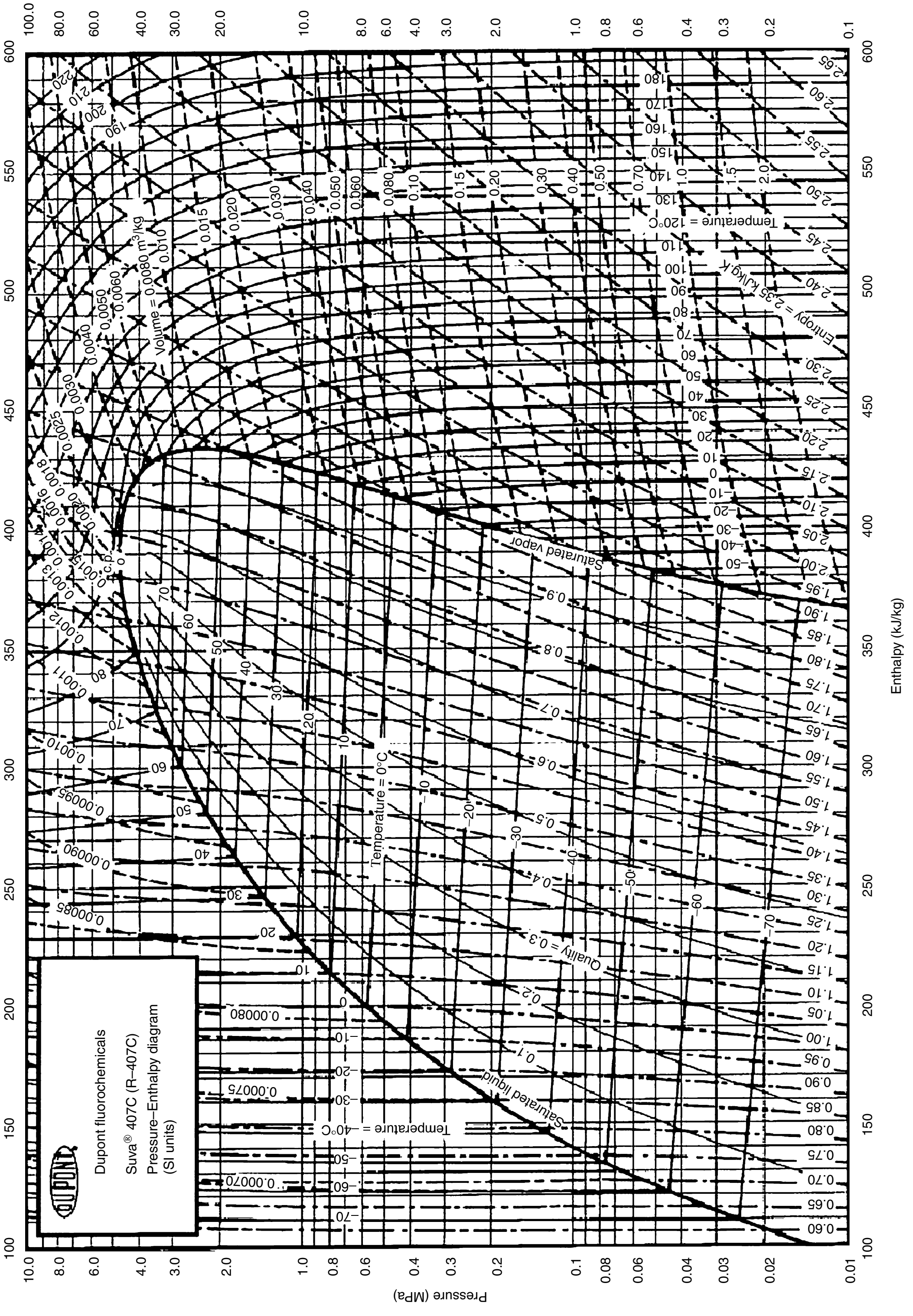


FIGURE A4.4 Pressure–enthalpy diagram for refrigerant R-407C.

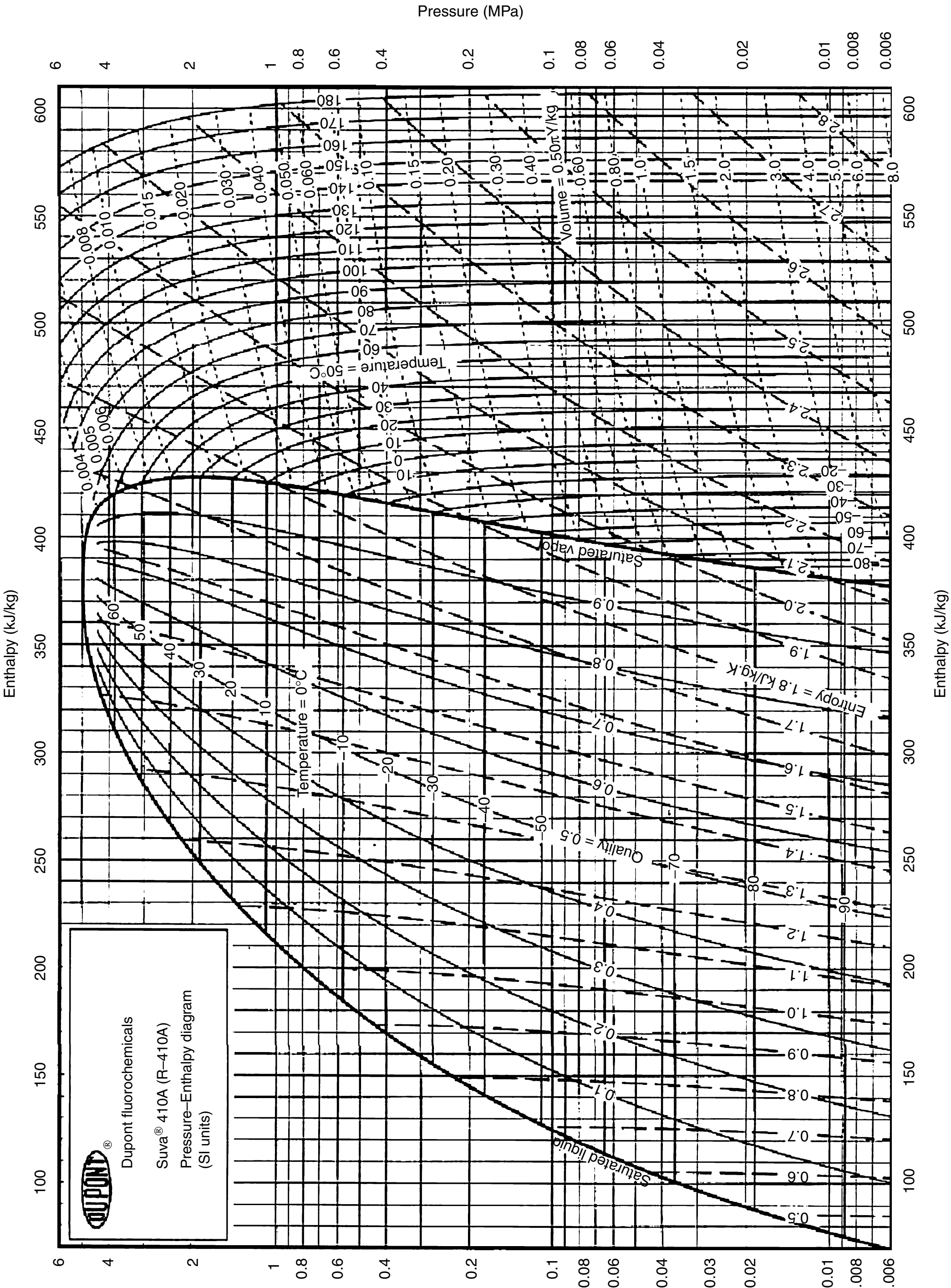


FIGURE A4.5 Pressure–enthalpy diagram for refrigerant R-410A.

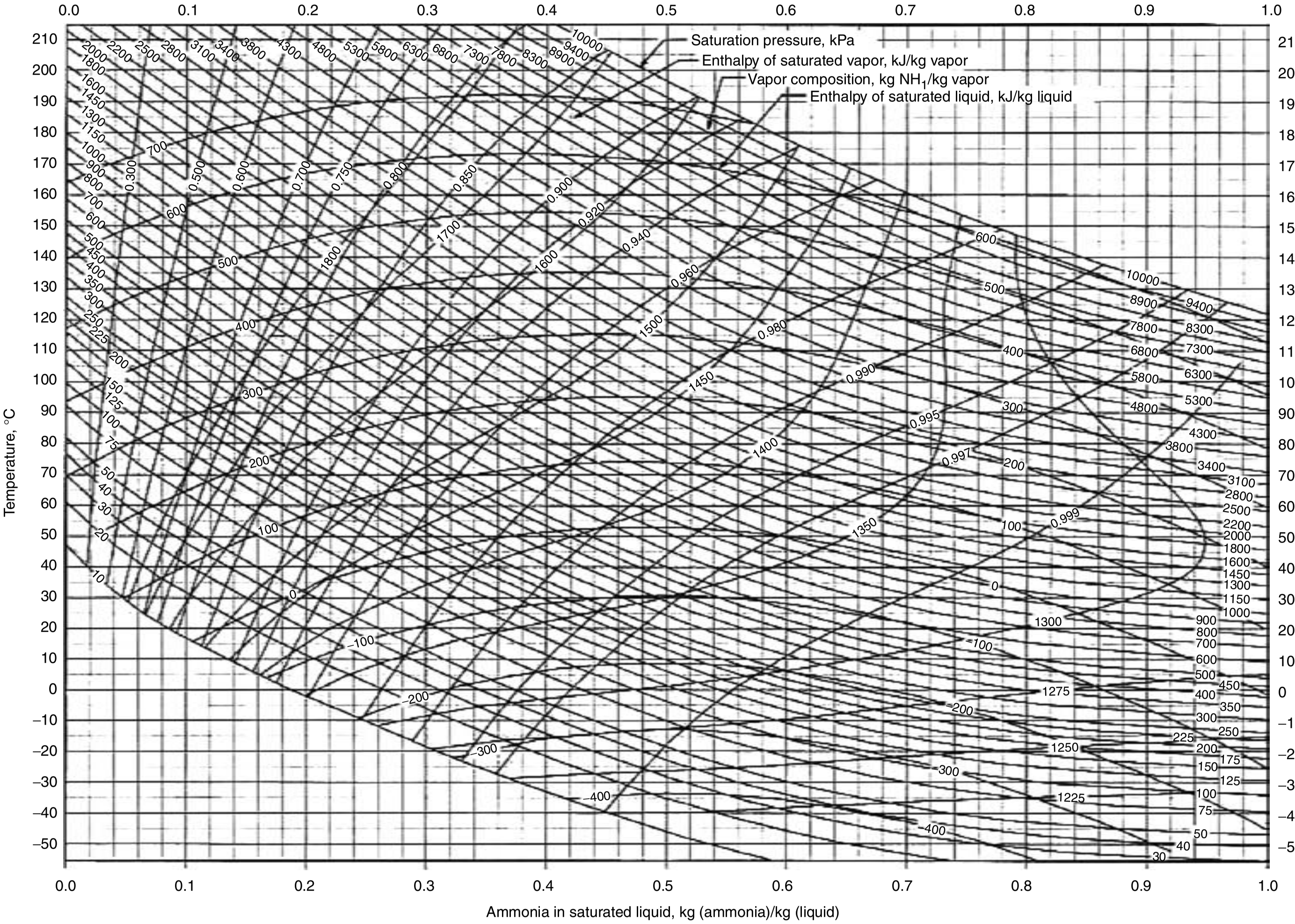
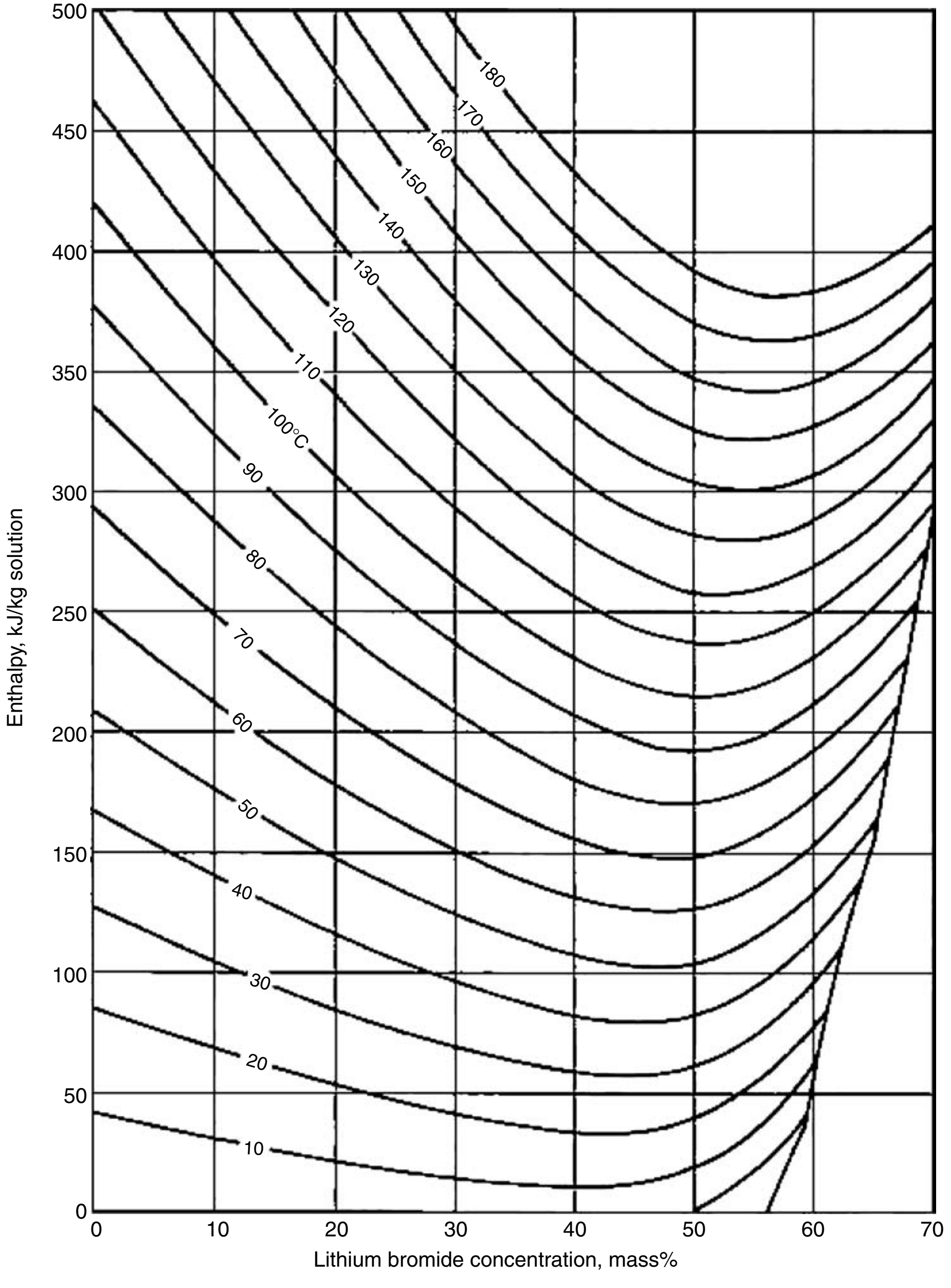


FIGURE A4.6 Enthalpy–concentration diagram for ammonia/water solutions prepared by Kwang Kim and Keith Herold, Centre for Environmental Energy Engineering, University of Maryland at Colleage Park.



Equations Concentration range 40 < x < 70% LiBr Temperature range 15 < t < 165°C

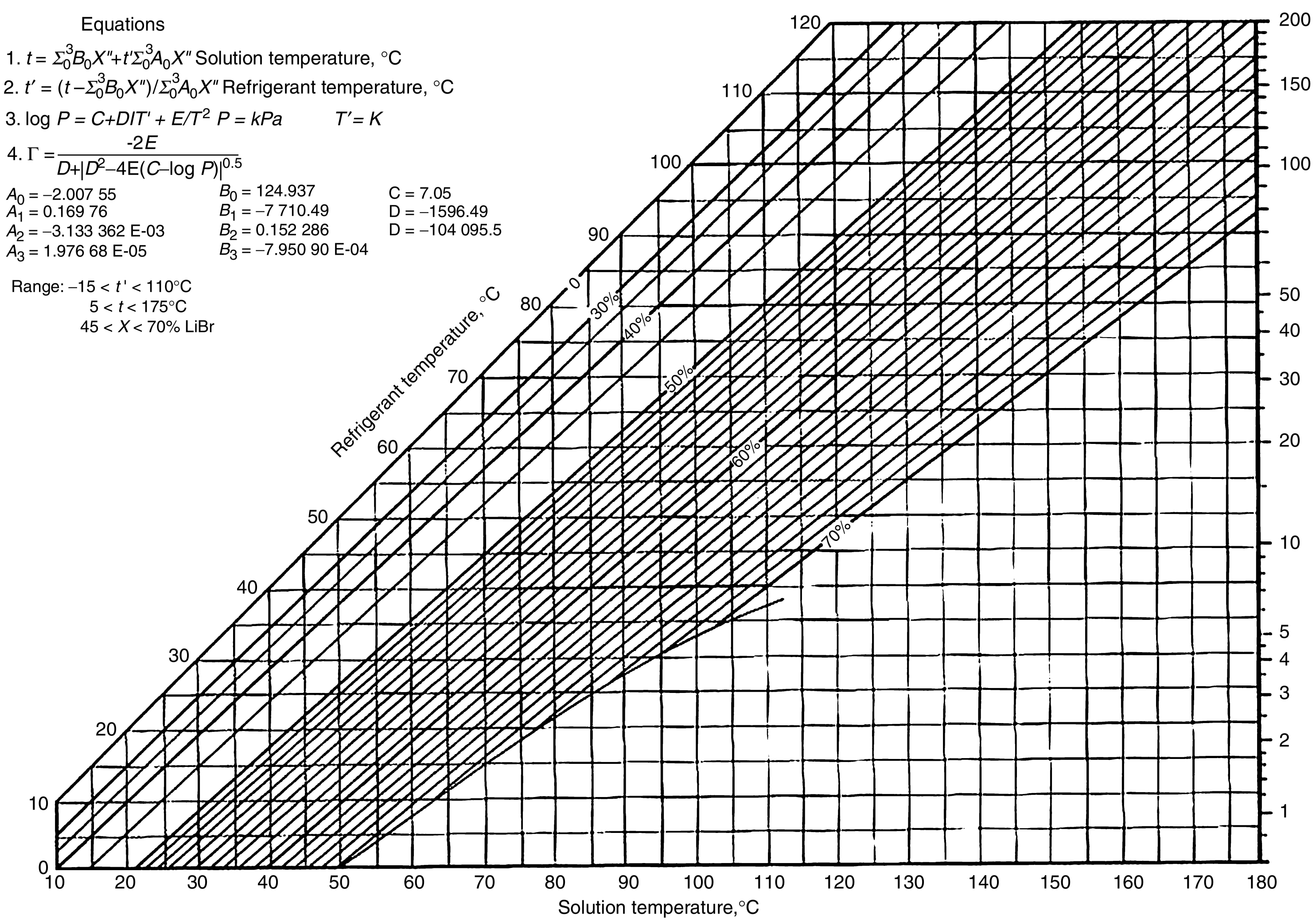
$h = \Sigma_0^4 A_n X^7 + \mathrm{r}\Sigma_0^4 B_n X^n + \mathrm{r}^2\Sigma_0^4 C_p X^n$ in kJ/kg, where t = °C and X = %LiBr

$A_0 = -2024.33$
$A_1 = 163.309$
$A_2 = -4.88161$
$A_3 = 6.302948$ E-2
$A_4 = -2.913705$ E-4

$B_0 = 18.2829$
$B_1 = -1.1691757$
$B_2 = 3.248041$E-2
$B_3 = -4.034184$ E-4
$B_4 = 1.8520569$ E-6

$C_0 = -3.7008214$ E-2
$C_1 = 2.8877666$ E-3
$C_2 = -8.1313015$ E-5
$C_3 = 9.9116628$ E-7
$C_4 = -4.4441207$ E-9

FIGURE A4.7 Enthalpy–concentration diagram for water/lithium bromide solutions.



Equations

1. $t = \Sigma_0^3 B_0 X'' + t' \Sigma_0^3 A_0 X''$ Solution temperature, °C

2. $t' = (t - \Sigma_0^3 B_0 X'')/\Sigma_0^3 A_0 X''$ Refrigerant temperature, °C

3. $\log P = C + D/T' + E/T'^2$ $P = kPa$ $T' = K$

4. $\Gamma = \dfrac{-2E}{D + |D^2 - 4E(C - \log P)|^{0.5}}$

$A_0 = -2.007\ 55$
$A_1 = 0.169\ 76$
$A_2 = -3.133\ 362\ \text{E-03}$
$A_3 = 1.976\ 68\ \text{E-05}$

$B_0 = 124.937$
$B_1 = -7\ 710.49$
$B_2 = 0.152\ 286$
$B_3 = -7.950\ 90\ \text{E-04}$

C = 7.05
D = −1596.49
D = −104 095.5

Range: $-15 < t' < 110$°C
$5 < t < 175$°C
$45 < X < 70$% LiBr

FIGURE A4.8 Equilibrium chart for aqueous lithium bromide solutions reprinted by permission of Carrier Corp.

Index

Mechanical Engineering

Offering expert guidance on the planning and design of "green" technologies, the **Energy Management and Conservation Handbook** focuses on management strategies for better utilization of energy in buildings and industry as well as ways of improving energy efficiency at the end use. Summarizing proven energy efficient technologies in the building sector, it includes examples that highlight the cost-effectiveness of some of these technologies. Renowned authorities from around the globe share insights and modern points of view on a broad spectrum of topics.

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