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Energy Audits for Buildings

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Moncef Krarti
University of Colorado

16.1 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.

16.2 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 16.1 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 16.2 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.

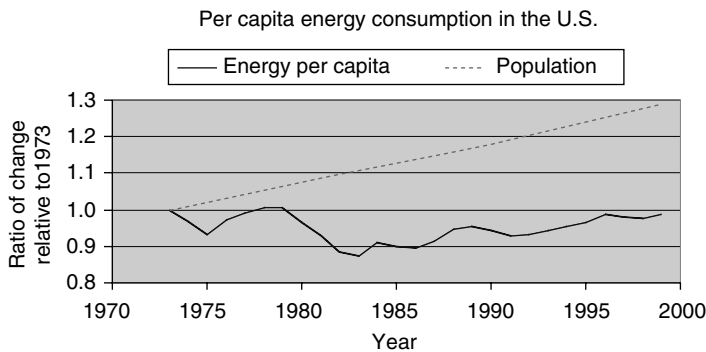


FIGURE 16.1 Per capita energy-use and population growth since 1973. (From EIA, *Annual Energy Review*, Department of Energy, Energy Information Administration, 1998. <http://www.doe.eia.gov>).

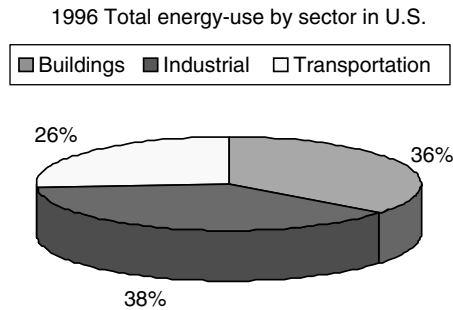


FIGURE 16.2 Distribution of U.S. energy consumption by end use sector. (From EIA, *Annual Energy Review*, Department of Energy, Energy Information Administration, 1998. <http://www.doe.eia.gov>).

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 16.1 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 16.2. 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 in 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 16.1 Energy Intensity by Principal Building Activity in kWh/m²

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'Énergie Dans les Régions Françaises*. Report from Centre d'Études et de Recherches Économiques sur l'Énergie 1997; Energy Information Administration (EIA), *Annual Energy Review*. Department of Energy. 1998. <http://www.doe.eia.gov> (accessed on 2005).

16.3 Energy Audit Procedures

16.3.1 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.

16.3.2 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 16.2 and Table 16.3 provide summaries of the energy audit procedure recommended respectively for commercial buildings and for industrial facilities (Karti 2000). Energy audits for thermal and electrical systems are separated because they are typically subject to different utility rates.

16.4 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.

16.4.1 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 16.2 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)
On-site survey	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	
	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
Energy-use baseline	Hot water/steam for specific applications (hospitals, swimming pools, etc.)	Energy-use for equipment
	Review architectural, mechanical, and control drawings	Energy-use for air handling
	Develop a base-case model (using any baselining method ranging from very simple to more detailed tools)	Energy-use for water distribution
Energy conservation measures	Calibrate the base-case model (using utility data or metered data)	Review architectural, mechanical, electrical, and control drawings
	Heat recovery system (heat exchangers)	Develop a base-case model (using any baselining method ranging from very simple to more detailed tools)
Energy conservation measures	Efficient heating system (boilers)	Calibrate the base-case model (using utility data or metered data)
	Temperature setback	Energy-efficient lighting
	EMCS	Energy-efficient equipment (computers)
	HVAC system retrofit	Energy-efficient motors
	DHW use reduction	HVAC system retrofit
	Cogeneration	EMCS
		Temperature setup
		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 contracting 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 16.3 Energy Audit Summary for Industrial Facilities

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

16.4.2 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.

16.4.3 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.

16.5 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).

16.5.1 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 16.3](#) 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 16.4](#). 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

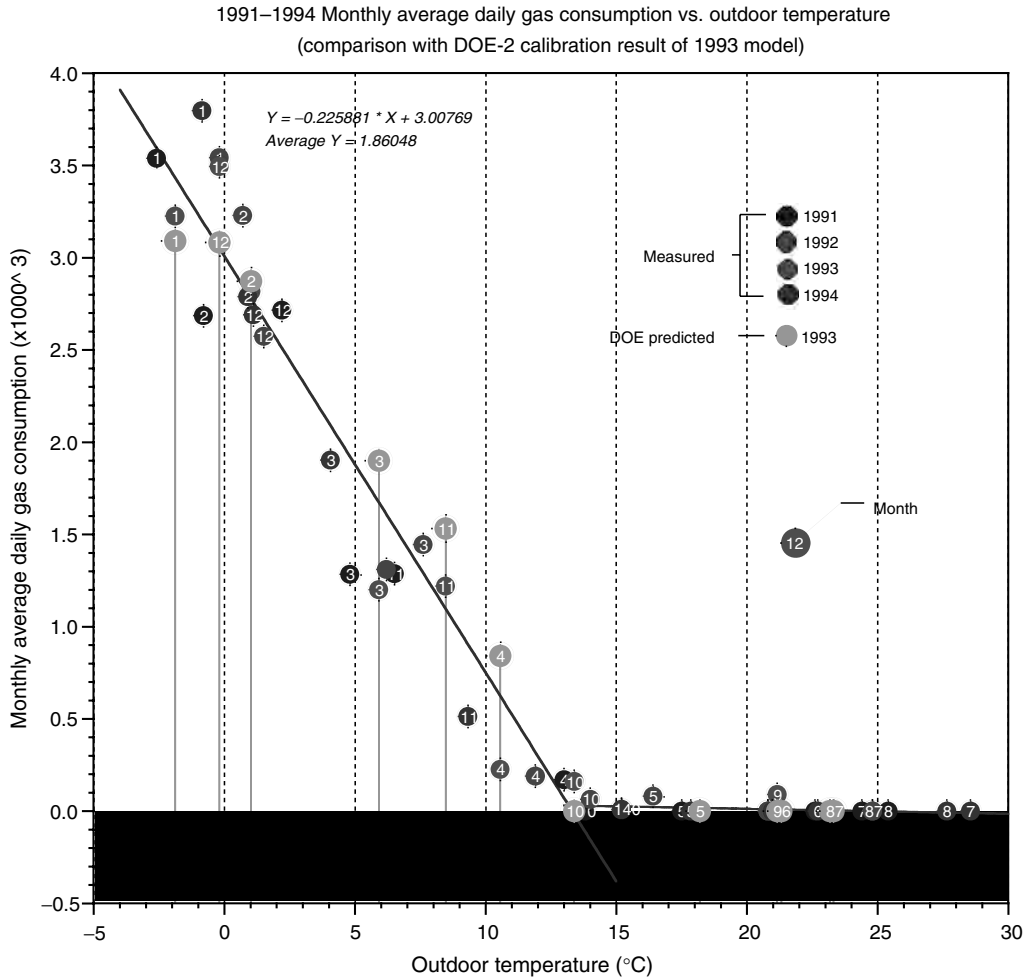


FIGURE 16.3 Estimation of the BLC based on a regression analysis of the monthly gas consumption. (From Krarti, M., *Energy Audit of Building Systems: An Engineering Approach*, CRC Press, Boca Raton, FL, 2000.)

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.

16.5.2 Ventilation and Indoor Air Quality

16.5.2.1 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

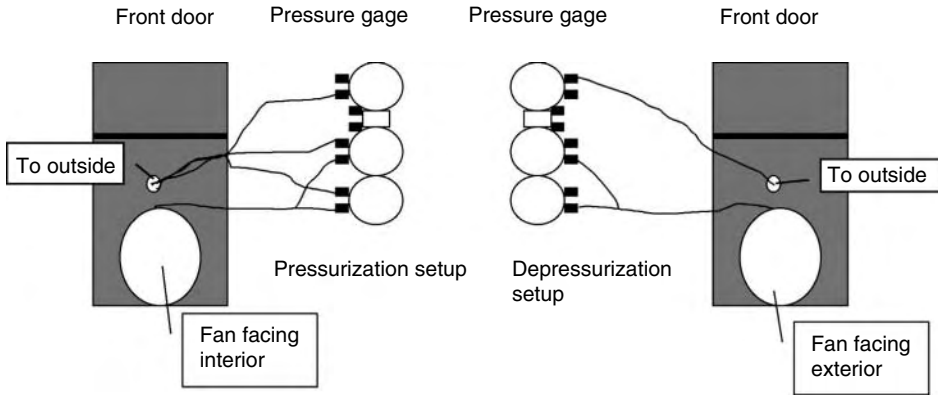


FIGURE 16.4 A blower door test setup for both pressurization and depressurization. (From Krarti, M., *Energy Audit of Building Systems: An Engineering Approach*, CRC Press, Boca Raton, FL, 2000.)

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 16.4 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 16.5. 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 CO₂ concentration level within the spaces. CO₂ 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 CO₂ set-point within the space. CO₂-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 CO₂ 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 CO₂-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 16.4 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 16.5 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 CO₂ 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).

16.5.2.2 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/sm² (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 16.5 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 16.5, significant fan energy savings can be

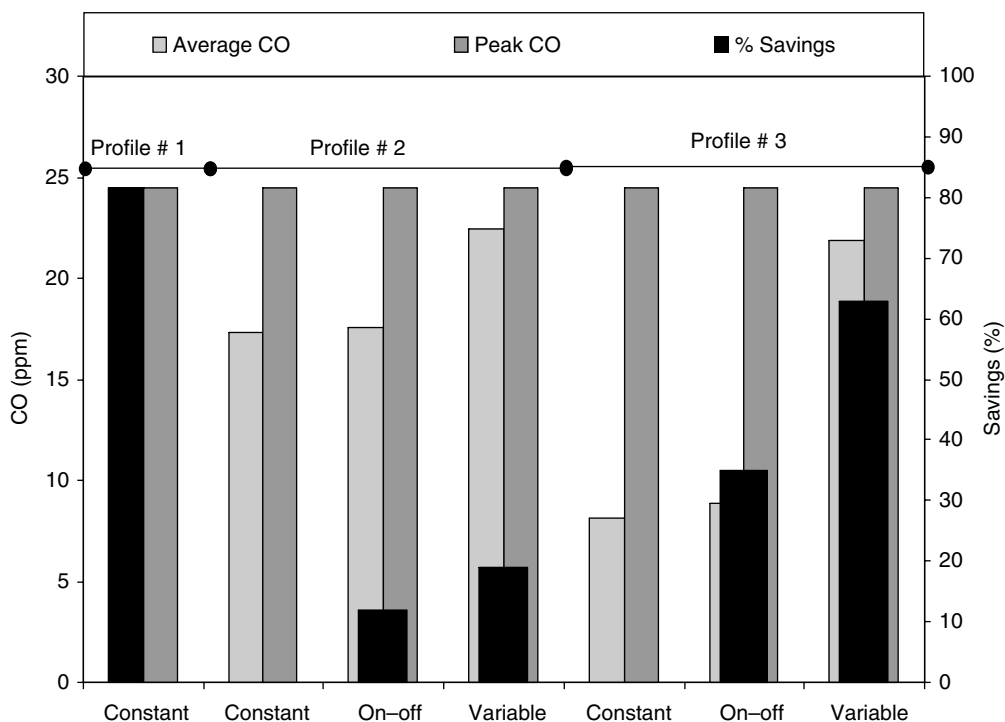


FIGURE 16.5 Typical energy savings and maximum CO level obtained for demand CO ventilation controls. (From Krarti, M., Ayari, A., and Grot, D., *Ventilation Requirements for Enclosed Vehicular Parking Garages*, Final Report for ASHRAE RP-945, American Society of Heating, Refrigerating, and Air Conditioning 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 16.6 indicates three types of car movement profiles considered in the analysis considered by Krarti, Ayari and Grot (1999).

16.5.3 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.

16.5.3.1 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.

16.5.3.2 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

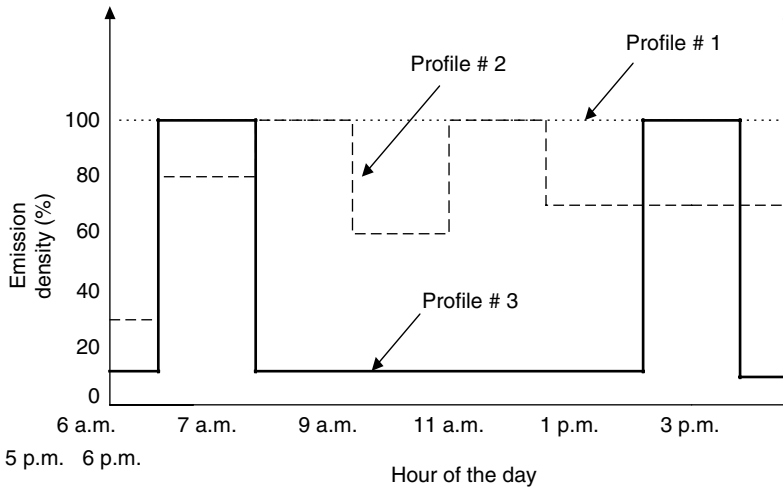


FIGURE 16.6 Car movement profiles used in the analysis conducted by Krarti et al. (From Krarti, M., Ayari, A., and Grot, D., *Ventilation Requirements for Enclosed Vehicular Parking Garages*, Final Report for ASHRAE RP-945, American Society of Heating, Refrigerating, and Air Conditioning Engineering, 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:

$$f_d = b[1 - \exp(-a\tau_w A_w/A_p)] \frac{A_p}{A_f}, \quad (16.1)$$

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 16.1 are coefficients that depends only on the building location and are given by Table 16.6 for various sites throughout the world.

16.5.3.3 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.

16.5.3.4 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 16.6 Coefficients a and b of Equation 16.1 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 16.5 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.

16.5.4 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.

16.5.5 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 16.7 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 16.7 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.

16.5.6 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 :

$$R_e = \frac{(\text{PeakEnergyRate}/\text{kWh})}{\text{Off - Peak Energy Rate}/(\text{kWh})}. \quad (16.2)$$

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

$$R_d = \frac{(\text{PeakDemandRate}/\text{kW})}{\text{Off - Peak Demand Rate}/(\text{kW})}. \quad (16.3)$$

Figure 16.7 and Figure 16.8 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/m²) and the time-of-use rate has an 8-h on-peak period (Morgan and Krarti 2005).

16.5.7 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 16.8 provides typical water use of conventional and water-efficient fixtures for various end uses. In addition, Table 16.8 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.

16.5.8 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:

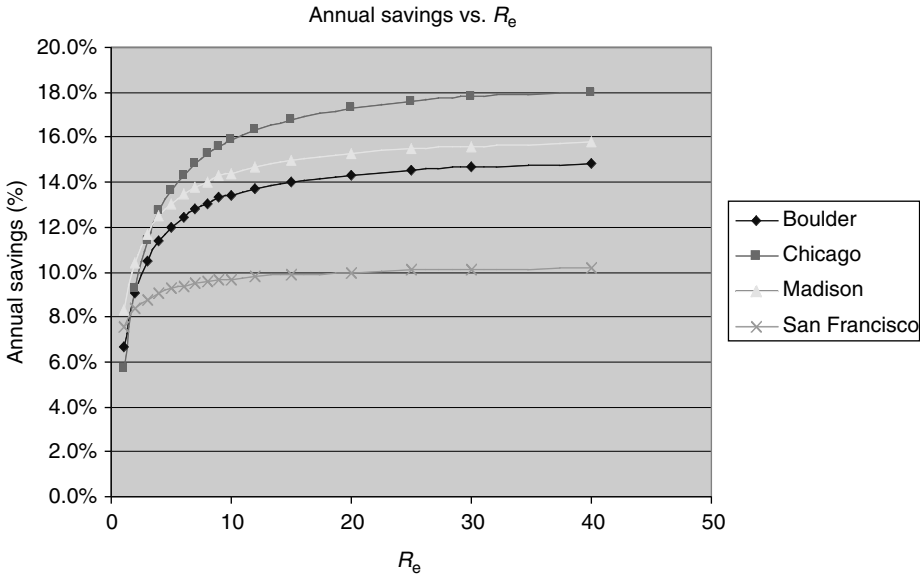


FIGURE 16.7 Annual energy cost savings due to precooling relative to conventional controls as a function of R_e . (From Morgan, S. and Krarti, M., *Impact of Electricity Rate Structures on the Energy Cost Savings of Precooling Controls for Office Buildings, Building and Environment* submitted, 2005.)

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)

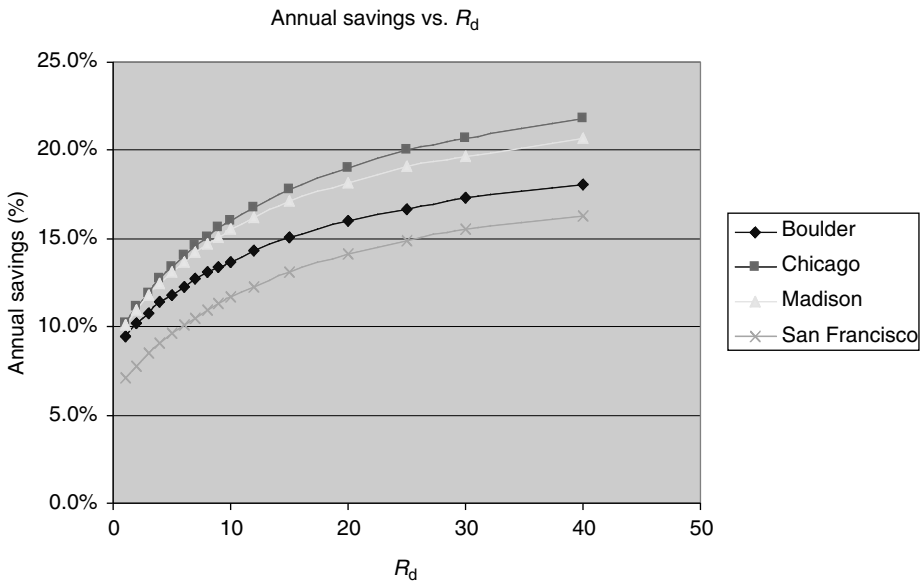


FIGURE 16.8 Annual energy cost savings due to precooling relative to conventional controls as a function of R_d . (From Morgan, S. and Krarti, M., *Impact of Electricity Rate Structures on the Energy Cost Savings of Precooling Controls for Office Buildings, Building and Environment* submitted, 2005.)

TABLE 16.8 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 as 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 as hospitals and universities.

16.6 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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