Related Commercial Resources

CHAPTER 3. COMMERCIAL AND PUBLIC BUILDINGS

THIS chapter contains technical, environmental, and design considerations to assist the design engineer in the proper application of HVAC systems and equipment for commercial and public buildings.

Other relevant ASHRAE resources include the following.

- **ASHRAE's Epidemic Task Force (ETF)** (www.ashrae.org/technical-resources/resources). Established in March 2020, the ETF has developed an array of guidance documents on engineering improvements to reduce the risk of infection in the built environment. One-page overviews of guidance for industrial settings, safe vaccine transportation, reducing exposure to airborne aerosols, and various applications can be found at www.ashrae.org/technical-resources/covid-19-one-page-guidance-documents.
- **ASHRAE Task Force for Building Decarbonization (TFBD)**. The ASHRAE position statement on reducing carbon in buildings is available at www.ashrae.org/about/position-documents. Research is ongoing to develop additional guidance, which is anticipated to begin release in 2023.
- **Operational excellence.** To help ensure that building HVAC systems are designed and installed in ways that achieve excellent operation throughout the building's life, an ASHRAE Presidential Elect Advisory Committee led by ASHRAE President Darryl Boyce developed and released *Designing for Operational Excellence—Intentional Design for Effective Operation and Maintenance* (ASHRAE 2022).

1. OFFICE BUILDINGS

General Design Considerations

Despite cyclical market fluctuations, office buildings are considered the most complex and competitive segments of real estate development. Survey data of 824,000 office buildings (EIA 2003) demonstrate the distribution of the U.S. office buildings by the numbers and the area, as shown in Table 1.

According to Gause (1998), an office building can be divided into the following categories:

Table 1 Data for U.S. Office Buildings

	Number of Buildings (Thousands)	Percent of Total Number of Buildings	Total Floor Space (Million ft^2)	Percent of Total Floor Space
Total	824	100.0	12,208	100.0
1,001 to 5,000 ft^2	503	61.0	1,382	11.32
5,001 to 10,000 ft^2	127	15.4	938	7.68
10,001 to 25,000 ft^2	116	14.1	1,887	15.46
25,001 to 50,000 ft^2	43	5.2	1,506	12.34
50,001 to 100,000 ft^2	17	2.1	1,209	9.90
100,001 to 200,000 ft^2	11	1.3	1,428	11.70
200,001 to 500,00 ft^2	5	0.6	1,493	12.23
>500,000 ft^2	2	0.2	2,365	19.37

Source: EIA (2003).

Class. The most basic feature, class represents the building's quality by taking into account variables such as age, location, building materials, building systems, amenities, lease rates, etc. Office buildings are of three classes: A, B, and C. **Class A** is generally the most desirable building, located in the most desirable locations, and offering first-rate design, building systems, and amenities. **Class B** buildings are located in good locations, have little chance of functional obsolescence, and have reasonable management. **Class C** buildings are typically older, have not been modernized, are often functionally obsolete, and may contain asbestos. These low standards make Class C buildings potential candidates for demolition or conversion to another use.

Size and Flexibility. Office buildings are typically grouped into three categories: **high rise** (16 stories and above), **mid rise** (four to 15 stories), and **low rise** (one to three stories).

Location. An office building is typically in one of three locations: **downtown** (usually high rises), **suburban** (low- to mid-rise buildings), or **business/industrial park** (typically one- to three-story buildings).

Floorplate (Floor Space Area). Size typically ranges from 18,000 to 30,000 ft^2 and averages from 20,000 to 25,000 ft^2.

Use and Ownership. Office buildings can be single tenant or multitenant. A single-tenant building can be owned by the tenant or leased from a landlord. From an HVAC&R systems standpoint, a single tenant/owner is more cautious considering issues such as life-cycle cost and energy conservation. In many cases, the systems are not selected based on the lowest first cost but on life-cycle cost. Sometimes, the developer may wish to select a system that allows individual tenants to pay directly for the energy they consume.

Building Features and Amenities. Examples typically include parking, telecommunications, HVAC&R, energy management, restaurants, security, retail outlets, and health club.

Typical areas that can be found in office buildings are

Offices

- Offices: (private or semiprivate acoustically and/or visually).
- Conference rooms

Employee/Visitor Support Spaces

- Convenience store, kiosk, or vending machines
- Lobby: central location for building directory, schedules, and general information
- Atria or common space: informal, multipurpose recreation and social gathering space
- Cafeteria or dining hall
- Private toilets or restrooms
- Child care centers
- Physical fitness area
- Interior or surface parking areas

Administrative Support Spaces

- May be private or semiprivate acoustically and/or visually.

Operation and Maintenance Spaces

- General storage: for items such as stationery, equipment, and instructional materials
- Food preparation area or kitchen
- Computer/information technology (IT) closets
- Maintenance closets
- Mechanical and electrical rooms

A well-designed and functioning HVAC system should provide the following:

- Comfortable and consistent temperature and humidity
- Adequate amounts of outdoor air at all time to satisfy ventilation requirements
- Remove odors and contaminates from circulated air

The major factors affecting sizing and selection of the HVAC systems are as follows:

- Building size, shape and number of floors
- Amount of exterior glass
- Orientation, envelope
- Internal loads, occupants, lighting
- Thermal zoning (number of zones, private offices, open areas, etc.)

Office HVAC systems generally range from small, unitary, decentralized cooling and heating up to large systems comprising central plants (chillers, cooling towers, boilers, etc.) and large air-handling systems. Often, several types of HVAC systems are applied in one building because of special requirements such as continuous operation, supplementary cooling, etc. In office buildings, the class of the building also affects selection of the HVAC systems. For example, in a class A office building, the HVAC&R systems must meet more stringent criteria, including individual thermal control, noise, and flexibility; HVAC systems such as single-zone constant-volume, water-source heat pump, and packaged terminal air conditioners (PTACs) might be inapplicable to this class, whereas properly designed variable-air-volume (VAV) systems can meet these requirements.

Design Criteria

A typical HVAC design criteria covers parameters required for thermal comfort, indoor air quality (IAQ), and sound. Thermal comfort parameters (temperature and humidity) are discussed in ASHRAE *Standard* 55 and Chapter 9 of the 2021 *ASHRAE Handbook—Fundamentals*. Ventilation and IAQ are covered by ASHRAE *Standard* 62.1, the user's manual for that standard (ASHRAE 2021), and Chapter 16 of the 2021 *ASHRAE Handbook—Fundamentals*. Sound and vibration are discussed in Chapter 49 of this volume and Chapter 8 of the 2021 *ASHRAE Handbook—Fundamentals*.

Thermal comfort is affected by air temperature, humidity, air velocity, and mean radiant temperature (MRT), as well as nonenvironmental factors such as clothing, gender, age, and physical activity. These variables and how they correlate to thermal comfort can be evaluated by the *Thermal Comfort Tool CD* (ASHRAE 2011) in conjunction with ASHRAE *Standard* 55. General guidelines for temperature and humidity applicable for areas in office buildings are shown in Table 2.

Table 2 Typical Recommended Indoor Temperature and Humidity in Office Buildings

	Indoor Design Conditions		
	Temperature, °F/ Relative Humidity, %		
Area	**Winter**	**Summer**	**Comments**
Offices, conference rooms, common areas	70.0 to 74.0	74.0 to 78.0	
	20 to 30%	50 to 60%	
Cafeteria	70.0 to 73.5	78.5	
	20 to 30%	50%	
Kitchen	70.0 to 73.5	84.0 to 88.0	No humidity control
Toilets	72.0		Usually not conditioned
Storage	64.0		No humidity control
Mechanical rooms	61.0		Usually not conditioned

All office, administration, and support areas need outdoor air for ventilation. Outdoor air is introduced to occupied areas and then exhausted by fans or exhaust openings, removing indoor air pollutants generated by occupants and any other building-related sources. ASHRAE *Standard* 62.1 is used as the basis for many building codes. To define the ventilation and exhaust design criteria, consult local applicable ventilation and exhaust standards. Table 3 provides recommendations for ventilation design based on the ventilation rate procedure method and filtration criteria for office buildings.

Table 3 Typical Recommended Design Criteria for Ventilation and Filtration for Office Buildings

Category	Ventilation and Exhaust[a,b]				Minimum Filtration Efficiency, MERV[c]
	Combined Outdoor Air (Default Value) cfm per Person	Occupant Density,[f] per 1000 ft^2	Outdoor Air		
			cfm/ft^2	cfm per Unit	
Office areas	17	5			6 to 8
Reception areas	7	30			6 to 8
Main entry lobbies	11	10			6 to 8
Telephone/data entry	6	60			6 to 8
Cafeteria	9	100			6 to 8
Kitchen[d,e]			0.7 (exhaust)		NA
Toilets				70 (exhaust)	NA
Storage[g]			0.12		1 to 4

Notes:

[a] Based on ASHRAE *Standard 62.1-2010, Tables 6-1 and 6-4. For systems serving multiple zones, apply multiple-zone calculations procedure. If DCV is considered, see the section on Demand Control Ventilation (DCV).*

[b] This table should not be used as the only source for design criteria. Governing local codes, design guidelines, ANSI/ASHRAE *Standard 62.1 and user's manual, (ASHRAE 2021) must be consulted.*

[c] MERV = minimum efficiency reporting values, based on ASHRAE *Standard* 52.2-2007.

[d] See Chapter 34 for additional information on kitchen ventilation. For kitchenette use 0.3 cfm/ft^2.

[e] Consult local codes for kitchen exhaust requirements.

[f] Use default occupancy density when actual occupant density is not known.

[g] This recommendation for storage might not be sufficient when the materials stored have harmful emissions.

Acceptable noise levels in office buildings are important for office personnel; see Table 4 and Chapter 49.

Load Characteristics

Office buildings usually include both peripheral and interior zone spaces. The peripheral zone extends 10 to 12 ft inward from the outer wall toward the interior of the building, and frequently has a large window area. These zones may be extensively subdivided. Peripheral zones have variable loads because of changing sun position and weather. These zones typically require heating in winter. During intermediate seasons, one side of the building may require cooling, while another side requires heating. However, the interior zone spaces usually require a fairly uniform cooling rate throughout the year because their thermal loads are derived almost entirely from lights, office equipment, and people. Interior space conditioning is often by systems that have VAV control for low- or no-load conditions.

Table 4 Typical Recommended Design Guidelines for HVAC-Related Background Sound for Areas in Office Buildings

Category	Sound Criteria[a,b] RC (N);QAI ≤ 5 dB	Comments
Executive and private office	25 to 35	
Conference rooms	25 to 35	
Teleconference rooms	≤25	
Open-plan office space	≤40	
	≤35	With sound masking
Corridors and lobbies	40 to 45	
Cafeteria	35 to 45	Based on service/support for hotels
Kitchen	35 to 45	Based on service/support for hotels
Storage	35 to 45	Based on service/support for hotels
Mechanical rooms	35 to 45	Based on service/support for hotels

Notes:

[a] Based on Table 1 in Chapter 49.

[b] RC (room criterion), QAI (quality assessment index) from Chapter 8 of the 2021 *ASHRAE Handbook—Fundamentals.*

Most office buildings are occupied from approximately 8:00 am to 6:00 pm; many are occupied by some personnel from as early as 5:30 am to as late as 7:00 pm. Some tenants' operations may require night work schedules, usually not beyond 10:00 pm. Office buildings may contain printing facilities, information and computing centers, or broadcasting studios, which could operate 24 h per day. Therefore, for economical air-conditioning design, the intended uses of an office building must be well established before design development.

Occupancy varies considerably. In accounting or other sections where clerical work is done, the maximum density is approximately one person per 75 ft^2 of floor area. Where there are private offices, the density may be as little as one person per 200 ft^2. The most serious cases, however, are the occasional waiting rooms, conference rooms, or directors' rooms, where occupancy may be as high as one person per 20 ft^2.

The lighting load in an office building can be a significant part of the total heat load. Lighting and normal equipment electrical loads average from 1 to 5 W/ft^2 but may be considerably higher, depending on the type of lighting and amount of equipment. Buildings with computer systems and other electronic equipment can have electrical loads as high as 5 to 10 W/ft^2. The amount, size, and type of computer equipment anticipated for the life of the building should be accurately appraised to size the air-handling equipment properly and provide for future installation of air-conditioning apparatus.

Total lighting heat output from recessed fixtures can be withdrawn by exhaust or return air and thus kept out of space-conditioning supply air requirements. By connecting a duct to each fixture, the most balanced air system can be provided. However, this method is expensive, so the suspended ceiling is often used as a return air plenum with air drawn from the space to above the suspended ceiling.

Miscellaneous allowances (for fan heat, duct heat pickup, duct leakage, and safety factors) should not exceed 12% of the total load.

Building shape and orientation are often determined by the building site, but some variations in these factors can increase refrigeration load. Shape and orientation should therefore be carefully analyzed in the early design stages.

Design Concepts

The variety of functions and range of design criteria applicable to office buildings have allowed the use of almost every available air-conditioning system. Multistory structures are discussed here, but the principles and criteria are similar for all sizes and shapes of office buildings.

Attention to detail is extremely important, especially in modular buildings. Each piece of equipment, duct and pipe connections, and the like may be duplicated hundreds of times. Thus, seemingly minor design variations may substantially affect construction and operating costs. In initial design, each component must be analyzed not only as an entity, but also as part of an integrated system. This systems design approach is essential for achieving optimum results.

As discussed under General Design Considerations, there are several classes of office buildings, determined by the type of financing required and the tenants who will occupy the building. Design evaluation may vary considerably based on specific tenant requirements; it is not enough to consider typical floor patterns only. Many larger office buildings include stores, restaurants, recreational facilities, data centers, telecommunication centers, radio and television studios, and observation decks.

Built-in system flexibility is essential for office building design. Business office procedures are constantly being revised, and basic building services should be able to meet changing tenant needs.

The type of occupancy may have an important bearing on air distribution system selection. For buildings with one owner or lessee, operations may be defined clearly enough that a system can be designed without the degree of flexibility needed for a less well-defined operation. However, owner-occupied buildings may require considerable design flexibility because the owner will pay for all alterations. The speculative builder can generally charge alterations to tenants. When different tenants occupy different floors, or even parts of the same floor, the degree of design and operation complexity increases to ensure proper environmental comfort conditions to any tenant, group of tenants, or all tenants at once. This problem is more acute if tenants have seasonal and variable overtime schedules.

Certain areas may have hours of occupancy or design criteria that differ substantially from those of the office administration areas; such areas should have their own air distribution systems and, in some cases, their own heating and/or refrigeration equipment.

Main entrances and lobbies are sometimes served by a separate and self contained system because they buffer the outdoor atmosphere and the building interior. Some engineers prefer to have a lobby summer temperature 4 to 6°F above office temperature to reduce operating cost and temperature shock to people entering or leaving the building. In cases where lobbies or main entrances have longer (or constant) operation, a dedicated/self-contained HVAC system is recommended to allow turning off other building systems.

The unique temperature and humidity requirements of server rooms or computer equipment/data processing installations, and the fact that they often run 24 h per day for extended periods, generally warrant separate refrigeration and air distribution systems. Separate back-up systems may be required for data processing areas in case the main building HVAC system fails. Chapter 20 has further information.

The degree of air filtration required should be determined. Service cost and effect of air resistance on energy costs should be analyzed for various types of filters. Initial filter cost and air pollution characteristics also need to be considered. Activated charcoal filters for odor control and reduction of outdoor air requirements are another option to consider.

Providing office buildings with continuous 100% outdoor air (OA) is seldom justified, so most office buildings are designed to minimize outdoor air use, except during economizer operation. However, attention to indoor air quality may dictate higher levels of ventilation air. In addition, the minimum volume of outdoor air should be maintained in variable-volume air-handling systems. Dry-bulb- or enthalpy-controlled economizer cycles should be considered for reducing energy costs. Consult ASHRAE *Standard* 90.1 for the proper air economizer system (dry-bulb or enthalpy). When an economizer cycle is used, systems should be zoned so that energy is not wasted by heating outdoor air. This is often accomplished by a separate air distribution system for the interior and each major exterior zone. A dedicated outdoor air system (DOAS) can be considered where the zones are served by in-room terminal systems (fan coils, induction unit systems, etc.) or decentralized systems [e.g., minisplit HVAC, water-source heat pump (WSHP)]. Because the outdoor air supply is relatively low in office buildings, air-to-air heat recovery is not cost effective; instead, a DOAS with enhanced cooling and dehumidification systems can be used.

These systems typically use hot-gas reheat or other means of free reheat (e.g., heat pipes, plate-frame heat exchangers). In hot, humid climates, these systems can significantly improve space conditions. By having a DOAS, the OA supply can be turned off during unoccupied hours (which can be significant in office buildings). In unoccupied mode, the in-room unit needs to maintain only the desired space conditions (e.g., night/weekend setback temperature).

High-rise office buildings have traditionally used perimeter fan-powered VAV terminals, induction, or fan-coil systems. Separate all-air systems have generally been used for the interior and/or the exterior for the fan-powered VAV perimeter terminals; modulated air diffusers and fan-powered perimeter unit systems have also been used. If variable-air-volume systems serve the interior, perimeters are usually served by variable-volume fan-powered terminals, typically equipped with hydronic (hot-water) or electric reheat coils. In colder climates, perimeter baseboard heaters are commonly applied. Baseboards are typically installed under windows to minimize the effect of the cold surface.

Many office buildings without an economizer cycle have a bypass multizone unit installed on each floor or several floors with a heating coil in each exterior zone duct. VAV variations of the bypass multizone and other floor-by-floor, all-air, or self-contained systems are also used. These systems are popular because of their low fan power and initial cost, and the energy savings possible from independent operating schedules between floors occupied by tenants with different operating hours.

Perimeter radiation or infrared systems with conventional, single-duct, low-velocity air conditioning that furnishes air from packaged air-conditioning units may be more economical for small office buildings. The need for a perimeter system, which is a function of exterior glass percentage, external wall thermal value, and climate severity, should be carefully analyzed.

A perimeter heating system separate from the cooling system is preferable, because air distribution devices can then be selected for a specific duty rather than as a compromise between heating and cooling performance. The higher cost of additional air-handling or fan-coil units and ductwork may lead the designer to a less expensive option, such as fan-powered terminal units with heating coils serving perimeter zones in lieu of a separate heating system. Radiant ceiling panels for perimeter zones are another option.

Interior space use usually requires that interior air-conditioning systems allow modification to handle all load situations. Variable-air-volume systems are often used. When using these systems, low-load conditions should be carefully evaluated to determine whether adequate air movement and outdoor air can be provided at the proposed supply air temperature without overcooling. Increases in supply air temperature tend to nullify energy savings in fan power, which are characteristic of VAV systems. Low-temperature air distribution for additional savings in transport energy is seeing increased use, especially when coupled with an ice storage system.

In small to medium-sized office buildings, air-source heat pumps or minisplit systems (cooling only, heat pump, or combination) such as variable refrigerant flow (VRF) may be chosen. VRF systems that can cool and heat simultaneously are available and allow users to provide heating in perimeter zones and cooling in interior zones in a similar fashion to four-pipe fan coil (FPFC) systems. In larger buildings, water-source heat pump (WSHP) systems are feasible with most types of air-conditioning systems. Heat removed from core areas is rejected to either a cooling tower or perimeter circuits. The water-source heat pump can be supplemented by a central heating system or electrical coils on extremely cold days or over extended periods of limited occupancy. Removed excess heat may also be stored in hot-water tanks. Note that in-room systems (e.g., VRF, WSHP) might need a DOAS to provide the required outdoor air.

Many heat recovery or water-source heat pump systems exhaust air from conditioned spaces through lighting fixtures. This reduces required air quantities and extends lamp life by providing a much cooler ambient operating environment.

Suspended-ceiling return air plenums eliminate sheet metal return air ductwork to reduce floor-to-floor height requirements. However, suspended-ceiling plenums may increase the difficulty of proper air balancing throughout the building. Problems often connected with suspended ceiling return plenums include

- Air leakage through cracks, with resulting smudges

- Tendency of return air openings nearest to a shaft opening or collector duct to pull too much air, thus creating uneven air motion and possible noise
- Noise transmission between office spaces

Air leakage can be minimized by proper workmanship. To overcome drawing too much air, return air ducts can be run in the suspended ceiling pathway from the shaft, often in a simple radial pattern. Ends of ducts can be left open or dampered. Generous sizing of return air grilles and passages lowers the percentage of circuit resistance attributable to the return air path. This bolsters effectiveness of supply-air-balancing devices and reduces the significance of air leakage and drawing too much air. Structural blockage can be solved by locating openings in beams or partitions with fire dampers, where required.

Systems and Equipment Selection

Selection of HVAC equipment and systems depends on whether the facility is new or existing, and whether it is to be totally or partially renovated. For minor renovations, existing HVAC systems are often expanded in compliance with current codes and standards with equipment that matches the existing types. For major renovations or new construction, new HVAC systems and equipment should be installed. When applicable, the remaining useful life of existing equipment and distribution systems should be considered.

HVAC systems and equipment energy use and associated life cycle costs should be evaluated. Energy analysis may justify new HVAC equipment and systems when an acceptable return on investment can be shown. The engineer must review all assumptions in the energy analysis with the owner. Other considerations for existing facilities are (1) whether the central plant is of adequate capacity to handle additional loads from new or renovated facilities; (2) age and condition of existing equipment, pipes, and controls; and (3) capital and operating costs of new equipment.

Chapter 1 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* provides general guidelines on HVAC systems analysis and selection procedures. Although in many cases system selection is based solely on the lowest first cost, it is suggested that the engineer propose a system with the lowest life-cycle cost (LCC). LCC analysis typically requires hour-by-hour building energy simulation for annual energy cost estimation. Detailed first and maintenance cost estimates of proposed design alternatives, using sources such as R.S. Means (R.S. Means 2022a, 2022), can also be used for the LCC analysis along with software such as BLCC 5.3.22 (FEMP 2022). Refer to Chapters 38 and 60 and the Value Engineering and Life-Cycle Cost Analysis section of this chapter for additional information.

System Types. HVAC systems for office buildings may be centralized, decentralized, or a combination of both. Centralized systems typically incorporate secondary systems to treat the air and distribute it. The cooling and heating medium is typically water or brine that is cooled and/or heated in a primary system and distributed to the secondary systems. Centralized systems comprise the following systems:

Secondary Systems

- Air handling and distribution (see Chapter 4 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*)
- In-room terminal systems (see Chapter 5 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*)
- Dedicated outdoor air systems (DOAS) with chilled water for cooling and hot water, steam, or electric heat for heating (for special areas when required)

Primary Systems

- Central cooling and heating plant (see Chapter 3 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*)

More detailed information on systems selection by application can be found in Table 5.

Typical decentralized systems (dedicated systems serving a single zone, or packaged systems such as packaged variable air volume) include the following:

- Water-source heat pumps (WSHP), also known as water-loop heat pumps (WLHP)
- Geothermal heat pumps (e.g., groundwater heat pumps, ground-coupled heat pumps)
- Hybrid geothermal heat pumps (combination of groundwater heat pumps, ground-coupled heat pumps, and an additional heat rejection device) for cases with limited area for the ground-coupled heat exchanger or where it is economically justified
- Packaged single-zone and variable-volume units
- Light commercial split systems

- Minisplit and variable refrigerant flow (VRF) units

Chapters 2, 9, 48, and 49 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* provide additional information on decentralized HVAC systems. Additional information on geothermal energy can be found in Chapter 35 of this volume.

Whereas small office buildings (<25,000 ft^2) normally apply packaged unitary and split systems equipment, larger office buildings can use a combination of packaged, unitary, split, and/or centralized systems, or large packaged rooftop systems. The building class also must be considered during system selection.

Systems Selection by Application. Table 5 shows the applicability of several systems for office buildings.

Special Systems

The following is a list of systems that can be considered for special areas in office buildings. Chapter 58 of this volume, Chapter 6 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*, and Skistad et al. (2002) provide additional information of these systems.

- Displacement ventilation
- Underfloor air distribution (UFAD)
- Active (induction) and passive chilled beams

Demand-Controlled Ventilation (DCV). Demand-controlled ventilation can reduce the operating cost of HVAC systems. Areas such as auditoriums, large conference rooms, and other spaces designed for large numbers of occupants and intermittent occupancy can use DCV. This approach is most cost effective when one dedicated air handling system serves each of these zones. Special attention is required when DCV is applied to VAV systems. In these cases, it is insufficient to use only one CO_2 sensor in the return air plenum of the central AHU, because the readings are the average of all the zones. To address properly DCV in a VAV system, a CO_2 sensor is required in every controlled zone.

Spatial Requirements

Total office building electromechanical space requirements vary tremendously based on types of systems planned; however, the average is approximately 8 to 10% of the gross area. Clear height required for fan rooms varies from approximately 10 to 18 ft, depending on the distribution system and equipment complexity. On office floors, perimeter fan-coil or induction units require approximately 1 to 3% of the floor area. Interior air shafts and pipe chases require approximately 3 to 5% of the floor area. Therefore, ducts, pipes, and equipment require approximately 4 to 8% of each floor's gross area.

Where large central units supply multiple floors, shaft space requirements depend on the number of fan rooms. In such cases, one mechanical equipment room usually furnishes air requirements for 8 to 20 floors (above and below for intermediate levels), with an average of 12 floors. The more floors served, the larger the duct shafts and equipment required. This results in higher fan room heights and greater equipment size and mass.

The fewer floors served by an equipment room, the greater the flexibility in serving changing floor or tenant requirements. Often, one mechanical equipment room per floor and complete elimination of vertical shafts requires no more total floor area than fewer larger mechanical equipment rooms, especially when there are many small rooms and they are the same height as typical floors. Equipment can also be smaller, although maintenance costs are higher. Energy costs may be reduced with more equipment rooms serving fewer areas, because equipment can be shut off in unoccupied areas, and high-pressure ductwork is not required. Equipment rooms on upper levels generally cost more to install because of rigging and transportation logistics.

In all cases, mechanical equipment rooms must be thermally and acoustically isolated from office areas.

Cooling Towers. Cooling towers can be the largest single piece of equipment required for air-conditioning systems. Cooling towers require approximately 1 ft^2 of floor area per 400 ft^2 of total building area and are 13 to 40 ft high. If towers are located on the roof, the building structure must be able to support the cooling tower and dunnage, full water load (approximately 120 to 150 lb/ft^2), and seismic and wind load stresses.

Where cooling tower noise may affect neighboring buildings, tower design should include sound traps or other suitable noise baffles. This may affect tower space, mass of the units, and motor power. Slightly oversizing cooling towers can reduce noise and power consumption because of lower speeds and also the ability to reduce the condenser water temperature, which reduces cooling energy. The size increase may increase initial cost.

Table 5 Applicability of Systems to Typical Office Buildings

	Cooling/Heating Systems							Heating Only	
	Centralized			Decentralized					
Building Area/Stories	SZ[a]	VAV/Reheat	Fan Coil (Two- and Four-Pipe)	PSZ/SZ* Split/ VRF	PVAV/Reheat	WSHP	Geothermal Heat Pump and Hybrid Geothermal Heat Pump	Perimeter Baseboard/Radiators	Unit Heaters
<25,000 ft^2, one to three stories				X		X	X	X	Special areas
25,000 to 150,000 ft^2, one to five stories	X	X	X	X	X	X	X	X	Special areas
>150,000 ft^2, low rise and high rise	X	X	X			X	X	X	Special areas

* SZ = single zone PSZ = packaged single zone WSHP = water-source heat pump
VAV = variable-air-volume PVAV = packaged variable-air-volume VRF = variable refrigerant flow

Cooling towers are sometimes enclosed in a decorative screen for aesthetic reasons; therefore, calculations should ascertain that the screen has sufficient free area for the tower to obtain its required air quantity and to prevent recirculation.

If the tower is placed in a rooftop well or near a wall, or split into several towers at various locations, design becomes more complicated, and initial and operating costs increase substantially. Also, towers should not be split and placed on different levels because hydraulic problems increase. Finally, the cooling tower should be built high enough above the roof so that the bottom of the tower and the roof can be maintained properly.

Special Considerations

Office building areas with special ventilation and cooling requirements include elevator machine rooms, electrical and telephone closets, electrical switchgear, plumbing rooms, refrigeration rooms, and mechanical equipment rooms. The high heat loads in some of these rooms may require air-conditioning units for spot cooling.

In larger buildings with intermediate elevator, mechanical, and electrical machine rooms, it is desirable to have these rooms on the same level or possibly on two levels. This may simplify horizontal ductwork, piping, and conduit distribution systems and allow more effective ventilation and maintenance of these equipment rooms.

An air-conditioning system cannot prevent occupants at the perimeter from feeling direct sunlight. Venetian blinds and drapes are often provided but seldom used. External shading devices (screens, overhangs, etc.) or reflective glass are preferable.

Tall buildings in cold climates experience severe stack effect. The extra amount of heat provided by the air-conditioning system in attempts to overcome this problem can be substantial. The following features help combat infiltration from stack effect:

- Revolving doors or vestibules at exterior entrances
- Pressurized lobbies or lower floors
- Tight gaskets on stairwell doors leading to the roof
- Automatic dampers on elevator shaft vents
- Tight construction of the exterior skin
- Tight closure and seals on all dampers opening to the exterior

2. TRANSPORTATION CENTERS

Major transportation facilities include transit facilities (rail transit, bus terminals), airports, and cruise terminals. Other areas that can be found in transportation centers are airplane hangars and freight and mail buildings, which can be treated as warehouse facilities. Bus terminals are covered partially in this chapter, but Chapter 16 provides more detail.

Airports

Airports are large, complex, and highly profitable enterprise. Most U.S. airports are public nonprofits, run directly by government entities or by government-created authorities known as airport or port authorities. There are three main types of airports:

- **International airports** serving over 20 million passengers a year.
- **National airports** serving between 2 to 20 million passengers a year.
- **Regional airport** serving up to 2 million passengers a year.

Airports typically consists the following:

- Runways and taxiing areas
- Air traffic control buildings
- Aircraft maintenance buildings and hangars
- Passenger terminals and car parking (open, partially open, or totally enclosed)
- Freight warehouses
- Lodging facilities (hotels)

In addition, support areas such as administration buildings, central utility plants, and transit facilities (rail and bus) are common in airport facilities.

Areas such as hangars, hotels, and car parking are not covered in this section. Information about hotels and parking garages can be found in Chapters 7 and 16, respectively. Warehouses are discussed in the next section of this chapter.

Most terminals can be divided into the following sections and subsections:

Departure

- Entrance concourse
- Check-in and ticketing
- Security and passports
- Shops, restaurants, banks, medical services, conference and business facilities, etc.
- Departure lounge
- Departure gates

Arrival

- Arrival lounge
- Baggage claim
- Customs, immigration, and passport control
- Exit concourse

Cruise Terminals

Cruise terminals typically have three main areas: departure/arrival concourse, ticketing, and baggage handling. These areas are open and large, and are designed to provide acceptable thermal comfort to the passenger during embarkation and debarkation.

Design Criteria

Transportation centers consist of a variety of areas, such as administration, large open areas, shops, and restaurants. Design criteria for these areas should be based on information on relevant chapters from this volume or ASHRAE *Standard* 62.1.

Load Characteristics

Airports, cruise terminals, and bus terminals operate on a 24 h basis, with a reduced schedule during late night and early morning hours. To better understand the load characteristics of these facilities, computer-based building energy modeling and simulation tools should be used; this chapter provides basic information and references for energy modeling. Given the dynamic nature of transportation facilities, well-supported assumptions of occupancy schedules should be established during the analysis process.

Airports. Terminal buildings consist of large, open circulating areas, one or more floors high, often with high ceilings, ticketing counters, and various types of stores, concessions, and convenience facilities. Lighting and equipment loads are generally average, but occupancy varies substantially. Exterior loads are, of course, a function of architectural design. The largest single problem often is thermal drafts created by large entranceways, high ceilings, and long passageways that have openings to the outdoors.

Cruise Terminals. Freight and passenger docks consist of large, high-ceilinged structures with separate areas for administration, visitors, passengers, cargo storage, and work. The floor of the dock is usually exposed to the outdoors just above the water level. Portions of the sidewalls are often open while ships are in port. In addition, the large ceiling (roof) area presents a large heating and cooling load. Load characteristics of passenger dock terminals generally require roof and floors to be well insulated. Occasional heavy occupancy loads in visitor and passenger areas must be considered.

Bus Terminals. These buildings consist of two general areas: the terminal, which contains passenger circulation, ticket booths, and stores or concessions; and the bus loading area. Waiting rooms and passenger concourse areas are subject to a highly variable occupant load: density may reach 10 ft^2 per person and, at extreme periods, 3 to 5 ft^2 per person. Chapter 16 has further information on bus terminals.

Design Concepts

Heating and cooling is generally centralized or provided for each building or group in a complex. In large, open-circulation areas of transportation centers, any all-air system with zone control can be used. Where ceilings are high, air distribution is often along the side wall to concentrate air conditioning where desired and avoid disturbing stratified air. Perimeter areas may require heating by radiation, a fan-coil system, or hot air blown up from the sill or floor grilles, particularly in colder climates. Hydronic perimeter radiant ceiling panels may be especially suited to these high-load areas.

Airports. Airports generally consist of one or more central terminal buildings connected by long passageways or trains to rotundas containing departure lounges for airplane loading. Most terminals have portable telescoping-type loading bridges connecting departure lounges to the airplanes. These passageways eliminate heating and cooling problems associated with traditional permanent passenger-loading structures.

Because of difficulties in controlling the air balance and because of the many outdoor openings, high ceilings, and long, low passageways (which often are not air conditioned), the terminal building (usually air conditioned) should be designed to maintain a substantial positive pressure. Zoning is generally required in passenger waiting areas, in departure lounges, and at ticket counters to take care of the widely variable occupancy loads.

Main entrances may have vestibules and windbreaker partitions to minimize undesirable air currents in the building.

Hangars must be heated in cold weather, and ventilation may be required to eliminate possible fumes (although fueling is seldom permitted in hangars). Gas-fired, electric, and low- and high-intensity radiant heaters are used extensively in hangars because they provide comfort for employees at relatively low operating costs.

Hangars may also be heated by large air blast heaters or floor-buried heated liquid coils. Local exhaust air systems may be used to evacuate fumes and odors that occur in smaller ducted systems. Under some conditions, exhaust systems may be portable and may include odor-absorbing devices.

Cruise Terminals. In severe climates, occupied floor areas may contain heated floor panels. The roof should be well insulated, and, in appropriate climates, evaporative spray cooling substantially reduces the summer load. Freight docks are usually heated and well ventilated but seldom cooled.

High ceilings and openings to the outdoors may present serious draft problems unless the systems are designed properly. Vestibule entrances or air curtains help minimize cross drafts. Air door blast heaters at cargo opening areas may be quite effective.

Ventilation of the dock terminal should prevent noxious fumes and odors from reaching occupied areas. Therefore, occupied areas should be under positive pressure and cargo and storage areas exhausted to maintain negative air pressure. Occupied areas should be enclosed to simplify any local air conditioning.

In many respects, these are among the most difficult buildings to heat and cool because of their large open areas. If each function is properly enclosed, any commonly used all-air or large fan-coil system is suitable. If areas are left largely open, the best approach is to concentrate on proper building design and heating and cooling of the openings. High-intensity infrared spot heating is often advantageous (see Chapter 16 of the 2020 *ASHRAE Handbook—HVAC*

Systems and Equipment). Exhaust ventilation from tow truck and cargo areas should be exhausted through the roof of the dock terminal.

Bus Terminals. Conditions are similar to those for airport terminals, except that all-air systems are more practical because ceiling heights are often lower, and perimeters are usually flanked by stores or office areas. The same systems are applicable as for airport terminals, but ceiling air distribution is generally feasible.

Properly designed radiant hydronic or electric ceiling systems may be used if high-occupancy latent loads are fully considered. This may result in smaller duct sizes than are required for all-air systems and may be advantageous where bus-loading areas are above the terminal and require structural beams. This heating and cooling system reduces the volume of the building that must be conditioned. In areas where latent load is a concern, heating-only panels may be used at the perimeter, with a cooling-only interior system.

The terminal area air supply system should be under high positive pressure to ensure that no fumes and odors infiltrate from bus areas. Positive exhaust from bus loading areas is essential for a properly operating total system (see Chapter 16).

Systems and Equipment Selection

Given the size and magnitude of the systems in airports and cruise terminals, the selection of the HVAC equipment and systems tend to be centralized. Depending on the area served and site limitations, decentralized systems can also be considered for these specific cases.

Centralized systems typically incorporate secondary systems to treat and distribute air. The cooling and heating medium is typically water or brine that is cooled and/or heated in a primary system and distributed to the secondary systems. Centralized systems comprise the following systems:

Secondary Systems

- Air handling and distribution (see Chapter 4 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*)
- In-room terminal systems (see Chapter 5 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*)
- Secondary systems such as variable air volume (VAV) are common in airports. Small, single-zone areas can be treated by constant-volume systems or fan coils.

Primary Systems

- Central cooling and heating plant (see Chapter 3 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*)
- For cases where decentralized systems (dedicated systems serving a single zone or packaged systems such as packaged variable air volume) are
- Water-source heat pumps (WSHP) (also known as water-loop heat pumps or WLHP)
- Packaged single-zone and variable-volume units
- Light commercial split systems
- Mini-split and variable-refrigerant-flow (VRF) units

Special Considerations

Airports. Filtering outdoor air with activated charcoal filters should be considered for areas subject to excessive noxious fumes from jet engine exhausts. However, locating outdoor air intakes as remotely as possible from airplanes is a less expensive and more positive approach.

Where ionization filtration enhancers are used, outdoor air quantities are sometimes reduced because the air is cleaner. However, care must be taken to maintain sufficient amounts of outdoor air for space pressurization.

Cruise Terminals. Ventilation design must ensure that fumes and odors from forklifts and cargo in work areas do not penetrate occupied and administrative areas.

Bus Terminals. The primary concerns with enclosed bus loading areas are health and safety problems, which must be handled by proper ventilation (see Chapter 16). Although diesel engine fumes are generally not as noxious as gasoline fumes, bus terminals often have many buses loading and unloading at the same time, and the total amount of fumes and odors may be disturbing.

In terms of health and safety, enclosed bus loading areas and automobile parking garages present the most serious problems. Three major problems are encountered, the first and most serious of which is emission of carbon monoxide (CO) by cars and oxides of nitrogen (NO_x) by buses, which can cause serious illness and possibly death. Oil and gasoline fumes, which may cause nausea and headaches and can create a fire hazard, are also of concern. The third issue is lack of air movement and the resulting stale atmosphere caused by increased CO content in the air. This condition may cause headaches or grogginess. Most codes require a minimum ventilation rate to ensure that the CO concentration does not exceed safe limits. Chapter 16 covers ventilation requirements and calculation procedures for enclosed vehicular facilities in detail.

All underground garages should have facilities for testing the CO concentration or should have the garage checked periodically. Problems such as clogged duct systems; improperly operating fans, motors, or dampers; or clogged air intake or exhaust louvers may not allow proper air circulation. Proper maintenance is required to minimize any operational defects.

3. WAREHOUSES AND DISTRIBUTION CENTERS

General Design Considerations

Warehouses can be defined as facilities that provide proper environment for the purpose of storing goods and materials. They are also used to store equipment and material inventory at industrial facilities. At times, warehouses may be open to the public. The buildings are generally not air conditioned, but often have sufficient heat and ventilation to provide a tolerable working environment. In many cases, associated facilities occupied by office workers, such as shipping, receiving, and inventory control offices, are air conditioned. Warehouses must be designed to accommodate the loads of materials to be stored, associated handling equipment, receiving and shipping operations and associated trucking, and needs of operating personnel. Types of warehouses include the following:

- **Heated and unheated general warehouses** provide space for bulk, rack, and bin storage, aisle space, receiving and shipping space, packing and crating space, and office and toilet space. As indicated some areas are typically equipped with small-decentralized air-conditioning systems for the support personnel.
- **Conditioned general warehouses** are similar to heated and unheated general warehouses, but can provide space cooling to meet the stored goods’ requirements.
- **Refrigerated warehouses** are designed to preserve the quality of perishable goods and general supply materials that require refrigeration. This includes freeze and chill spaces, processing facilities, and mechanical areas. For information on this type of warehouse, see Chapters 23 and 24 in the 2022 *ASHRAE Handbook—Refrigeration*.
- **Controlled humidity (CH) and dry-air storage warehouses** are similar to general warehouses except that they are constructed with vapor barriers and contain humidity control equipment to maintain humidity at desired levels. For additional information, see Chapter 29 of Harriman et al. (2001).
- **Specialty warehouses** includes storing facilities with special and in some instances strict requirements for temperature, humidity, cleanliness, minimum ventilation rates, etc. These facilities are typically conditioned to achieve the required space conditions. These warehouses can be found in industrial and manufacturing facilities or can be standalone buildings. Examples include
  - Pharmaceutical and life sciences facilities. Good manufacturing practices (GMP) may be required.
  - Liquid storage (fuel and nonpropellants), flammable and combustible storage, radioactive material storage, hazardous chemical storage, and ammunition storage.
  - Automated storage and retrieval systems (AS/RS), which are designed for maximum storage and minimum personnel on site. They are built for lower-temperature operation with minimal heat and light needed, but require a tall structure with extremely level floors. In some cases, specialty HVAC equipment is required for servers and other computer areas in AS/RS facility.

Features already now common in warehouse designs are higher bays, sophisticated materials-handling equipment, broadband connectivity access, and more distribution networks. A wide range of storage alternatives, picking alternatives, material-handling equipment, and software exist to meet the physical and operational requirements. Warehouse spaces must also be flexible to accommodate future operations and storage needs as well as mission changes.

Areas that can be found in warehouses and distribution centers include the following:

- Storage areas
- Office and administrative areas
- Loading docks

- Light industrial spaces
- Computer/server rooms

Other areas can be site specific.

Design Criteria

Design criteria (temperature, humidity, noise, etc.) for warehouses are space specific; the designer should refer to the relevant sections and chapters (e.g., the section on Office Buildings for office and administration areas). For conditioned storage areas, the special requirements of the product stores dictate the design conditions.

Outdoor air for ventilation of office, administration, and support areas should be based on local code requirements or ASHRAE *Standard* 62.1. For general warehouses where special ventilation or minimum ventilation rates are not specifically defined, *Standard* 62.1 can be used as the criterion for minimum outdoor air. To define the specific ventilation and exhaust design criteria, consult local applicable ventilation and exhaust standards. Table 6-1 of *Standard* 62.1-2022 recommends 0.09 cfm/ft^2 of ventilation as a design criterion for warehouse ventilation, although this amount may be insufficient when stored materials have harmful emissions.

Load Characteristics

Given the variety of warehouses facilities, every case should be analyzed carefully. In general, internal loads from lighting, people, and miscellaneous sources are low. Most of the load is thermal transmission and infiltration. An air-conditioning load profile tends to flatten where materials stored are massive enough to cause the peak load to lag. In humid climates, special attention should be given to the sensible and latent loads' variations for cases where the warehouse or distribution center is conditioned or cooled by thermostatically controlled packaged HVAC equipment. In these climates, it is common to satisfy the space temperature (i.e., very low or no sensible cooling load), but, because of infiltration of moist air and without proper cooling (i.e., the cooling equipment is off), for space humidity to be unacceptably high.

Design Concepts

Most warehouses are only heated and ventilated. Forced-flow unit heaters may be located near entrances and work areas. Large central heating and ventilating units are also widely used. Even though comfort for warehouse workers may not be considered, it may be necessary to keep the temperature above 40°F to protect sprinkler piping or stored materials from freezing.

A building designed for adding air conditioning at a later date requires less heating and is more comfortable. For maximum summer comfort without air conditioning, excellent ventilation with noticeable air movement in work areas is necessary. Even greater comfort can be achieved in appropriate climates by adding roof-spray cooling. This can reduce the roof's surface temperature, thereby reducing ceiling radiation inside. Low- and high-intensity radiant heaters can be used to maintain the minimum ambient temperature throughout a facility above freezing. Radiant heat may also be used for occupant comfort in areas permanently or frequently open to the outdoors.

If the stored product requires specific inside conditions, an air-conditioning system must be added. Using only ventilation may help maintain lower space temperatures, but care should be taken not to damage the stored product with uncontrolled humidity. Direct or indirect evaporative cooling may also be an option.

Systems and Equipment Selection

Selection of HVAC equipment and systems depends on type of warehouse. As indicated previously, the warehouse might need only heating/cooling in admin areas, or in some cases, highly sophisticated HVAC systems to address special ambient conditions required by the product stored in this warehouse. The same principles and procedures of selecting the HVAC systems described in the office building section of this chapter should be followed.

Selection by Application. Table 6 depicts typical systems applied for warehouse facilities. Centralized systems refer to warehouses where central chilled-water and/or hot-water/steam system is available. Decentralized systems are typically direct expansion (DX) systems with gas-fired heating or other available heating source.

Special systems are typically required when special ambient conditions have to be maintained: usual examples are desiccant dehumidification, mechanical dehumidification, and humidification.

In hot and humid climates, a combination of desiccant-based dehumidification equipment along with standard DX, packaged, single-zone units can be considered. This approach allows separation of sensible cooling load from latent load, thereby enhancing humidity control under most ambient conditions, reducing energy consumption, and allowing optimal equipment sizing and use.

Table 6 Applicability of Systems to Typical Warehouse Building Areas

Warehouse Area	Cooling/Heating Systems		Heating Only	
	Centralized	Decentralized	Heating and Ventilating Units	Local Unit Heaters
	SZ	PSZ/SZ Split/VRF		
Storage areas	X	X	X	X
Office and administration areas	X	X		
Loading docks			X	X
Light industrial spaces	X	X	X	
Computer/server rooms	X (also CHW, CRAC Unit)	X (also DX, CRAC Unit)		

SZ = single zone
PSZ = packaged single zone
VRF = variable refrigerant flow
CHW = chilled water
CRAC = computer room air conditioning

Spatial Requirements

Total building electromechanical space requirements vary based on types of systems planned. Typically, the HVAC equipment can be roof mounted, slab, indoor, or ceiling mounted. Ductwork and air discharge plenums usually are not concealed; often, the systems are free discharge.

Special Considerations

Forklifts and trucks powered by gasoline, propane, and other fuels are often used inside warehouses. Proper ventilation is necessary to alleviate build-up of CO and other noxious fumes. Proper ventilation of battery-charging rooms for electrically powered forklifts and trucks is also required.

4. SUSTAINABILITY AND ENERGY EFFICIENCY

In the context of this chapter, sustainable refers to a building that minimizes the use of energy, water, and other natural resources and provides a healthy and productive indoor environment (e.g., IAQ, lighting, noise). The HVAC&R designer plays a major role in supporting the design team in designing, demonstrating, and verifying these goals, particularly in the areas of energy efficiency and indoor environmental quality (mainly IAQ).

Several tools and mechanisms are available to assist the HVAC&R designer in designing and demonstrating sustainable commercial facilities; see the References and Bibliography in this chapter, the Sustainability and Energy Efficiency section in Chapter 8, and Chapter 35 in the 2021 *ASHRAE Handbook—Fundamentals*. ASHRAE *Standard* 189.1 provides guidance toward sustainable solutions.

Energy Considerations

Energy standards such as ANSI/ASHRAE/IESNA *Standard* 90.1 and local energy codes should be followed for minimum energy conservation criteria. Note that additional aspects such as lighting, motors/drives, building envelope, and electrical services should also be considered for energy reduction. Energy procurement/supply-side opportunities should also be investigated for energy cost reduction. Table 18 in Chapter 8 depicts a list of selected energy conservation opportunities.

Energy Efficiency and Integrated Design Process for Commercial Facilities

The integrated design process (IDP) is vital for the design of high-performance commercial facilities. For background and details on integrated building design (IBD) and IDP, see Chapter 60.

Unlike the sequential design process (SDP), where the elements of the built solution are defined and developed in a systematic and sequential manner, IDP encourages holistic collaboration of the project team during the all phases of the project, resulting in cost-effective and environmentally friendly design. IDP responds to the project objectives, which typically are established by the owner before team selection. Typical IDP includes the following elements:

- Owner planning
- Predesign
- Schematic design

- Schematic design
- Design development
- Construction documents
- Procurement
- Construction
- Operation

Detailed information on each element can be found in Chapter 60.

In high-performance buildings, these objectives are typically sustainable sites, water efficiency, energy and atmosphere quality, materials and resources, and indoor environmental quality. These objectives are the main components of several rating systems. Energy use objectives are typically the following:

- Meeting minimum prescriptive compliance (mainly local energy codes, ASHRAE *Standard* 90.1, etc.)
- Improving energy performance by an owner-defined percentage beyond the applicable code benchmark
- Demonstrating minimum energy performance (or prerequisite) and enhanced energy efficiency (for credit points) for sustainable design rating [e.g., U.S. Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED®)]
- Providing a facility/building site energy density [e.g., energy utilization index (EUI)] less than an owner-defined target [e.g., U.S. Environmental Protection Agency (EPA) ENERGY STAR guidelines)
- Provide an owner-defined percentage of facility source energy from renewable energy

Building Energy Modeling

Building energy modeling has been one of the most important tools in the process of IDP and sustainable design. Building energy modeling uses sophisticated methods and tools to estimate the energy consumption and behavior of buildings and building systems. To better illustrate the concept of energy modeling, the difference between HVAC sizing and selection programs and energy modeling tools will be described.

Design, sizing selection, and equipment sizing tools are typically used for design and sizing of HVAC&R systems, normally at the **design** process. Examples include cooling/heating load calculations tools, ductwork design software, piping design programs, acoustics software, and selection programs for specific types of equipment. The results are used to specify cooling and heating capacities, airflow, water flow, equipment size, etc., during the design as defined and agreed by the client.

Energy modeling [also known as building modeling and simulation (BMS)] is used to model the building's thermal behavior and the building energy systems' performance. Unlike design tools, which are used for one design point (or for sizing), the building energy simulation analyzes the building and the building systems up to 8760 times: hour by hour, or even in smaller time intervals.

A building energy simulation tool is a computer program consisting of mathematical models of building elements and HVAC&R equipment. To run a building energy simulation, the user must define the building elements, equipment variables, energy cost, etc. The simulation engine then solves mathematical models of the building elements, equipment, and so on 8760 times (one for every hour), usually through a sequential process. Common results include annual energy consumption, annual energy cost, hourly profiles of cooling loads, and hourly energy consumption. Chapter 19 of the 2021 *ASHRAE Handbook—Fundamentals* provides detailed information on energy modeling techniques.

Typically, energy modeling tools must meet minimum requirements to be accepted by rating authorities such as USGBC or local building codes. The following is typical of minimum modeling capabilities:

- 8760 h per year
- Hourly variations in occupancy, lighting power, miscellaneous equipment power, thermostat set points, and HVAC system operation, defined separately for each day of the week and holidays
- Thermal mass effects
- Ten or more thermal zones
- Part-load performance curves for mechanical equipment
- Capacity and efficiency correction curves for mechanical heating and cooling equipment

- Air-side economizers with integrated control
- Design load calculations to determine required HVAC equipment capacities and air and water flow rates in accordance with generally accepted engineering standards and practice
- Tested according to ASHRAE *Standard* 140

Energy modeling is typically used in the following ways:

- As a decision support tool for energy systems in new construction and retrofit projects; that is, it allows analyzing several design alternatives and the selection of the optimal solution for a given criterion
- To provide vital information to the engineer about the building behavior and systems performance during design
- To demonstrates compliance with energy standards such as ASHRAE *Standard* 90.1 (energy cost budget method)
- To support USGBC LEED certification in the Energy and Atmosphere (EA) section
- To model existing buildings and systems and analyzing proposed energy conservation measures (ECMs) by performing calibrated simulation
- Demonstrate energy cost savings as part of measurements and verification (M&V) protocol (by using calibrated simulation procedures)

Energy modeling is used intensively in LEED for New Construction (USGBC 2009), Energy & Atmosphere (EA), prerequisite 2 (minimum energy performance), and for EA credit 1 (Optimize Energy Performance). An energy simulation program (with the requirements shown above) along with ASHRAE *Standard* 90.1 is used to perform whole-building energy simulation for demonstrating energy cost savings. The number of credits awarded is in correlation to the energy cost reduction.

Energy Benchmarking and Benchmarking Tools

Energy benchmarking is an important element of energy use evaluation and tracking. It involves comparing building normalized energy consumption to that of other similar buildings. The most common normalization factor is the gross floor area. Energy benchmarking is less accurate then other energy analysis methods, but can provide a good overall picture of relative energy use.

Relative energy use is commonly expressed by the energy utilization index (EUI), which is the energy use per unit area per year. Typically, EUI is defined in terms of Btu/ft^2 per year. In some cases, the user is interested in energy cost benchmarking, which is known as the cost utilization index (CUI). CUI units are \$/ft^2 per year. It is important to differentiate between site EUI (actual energy used on site) and source EUI (energy used at the energy source); about two-thirds of the primary energy that goes into an electric power plant is lost in the process as waste heat.

One of the most important sources of energy benchmarking data is the Commercial Building Energy Consumption Survey (CBECS) by the U.S. Department of Energy's Energy Information Administration (DOE/EIA). Table 2 of Chapter 37 shows an example of EUI calculated based on DOE/EIA 2003 CBECS; the mean site EUI for mixed-use office space is 88 kBtu/ft^2 · yr. Other EUIs for commercial facilities can be found in the same table.

Common energy benchmarking tools include the following:

- U.S. EPA ENERGY STAR Portfolio Manager (www.energystar.gov/benchmark)
- Lawrence Berkeley National Laboratory (LBNL) ARCH (poet.lbl.gov/arch/)
- CAL-ARCH for the state of California (poet.lbl.gov/cal-arch/)

Comprehensive information on energy benchmarking and available benchmarking tools can be found in Glazer (2006) and Chapter 37.

Combined Heat and Power in Commercial Facilities

Combined heat and power (CHP) plants and building cooling heating and power (BCHP) can be considered for large facilities such as large office buildings and campuses and airports when economically justifiable. Chapter 7 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* and other sources such as Meckler and Hyman (2010), Orlando (1996), and Petchers (2002) provide information on CHP systems. Additional Internet-based sources for CHP include the following:

- U.S. EPA Combined Heat and Power (CHP) Partnership at www.epa.gov/chp/; procedures for feasibility studies and evaluations for CHP integration are available at http://www.epa.gov/chp/project-development/index.html
- U.S. Department of Energy, Energy Efficiency and Renewable Energy at www.energy.gov/eere/amo/chp-deployment
- A database of CHP installations can be found at www.eea-inc.com/chpdata/index.html

Maor and Reddy (2008) show a procedure to optimize the size of the prime mover and thermally operated chiller for large office buildings by combining a building energy simulation program and CHP optimization tools.

CHP systems can be applied in large district cooling and heating facilities and infrastructure to use waste heat efficiently. The type of the prime mover is heavily dependent on the electrical and thermal loads, ability to use waste heat efficiently, and utility rates. Table 1 in Chapter 7 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* provides information on the applicability of CHP.

Renewable Energy

Renewable energy (RE) technologies, including solar, wind, and biomass, can be considered when applicable and economically justifiable. Renewable energy use can add LEED credits (USGBC 2009) under Energy and Atmosphere (credit 2), depending on the percentage of renewable energy used.

Given the increased number and popularity of solar systems, only these systems will be discussed in this chapter. Geothermal energy is also considered to be renewable energy; these systems are discussed earlier in this chapter, and in more detail in Chapter 35.

Solar/Photovoltaic. Photovoltaic (PV) technology is the direct conversion of sunlight to electricity using semiconductor devices called solar cells. Photovoltaic are almost maintenance-free and seem to have a long lifespan. Given the longevity, no pollution, simplicity, and minimal resources, this technology is highly sustainable, and the proper financing mechanisms can make this system economically justifiable.

Airport facilities can be considered good candidates for PV technology for the following reasons:

- Large, low-rise buildings with available roof for PV collectors
- Little or no shading
- Large open area (open areas, parking lots, etc.)
- Hours and seasons of operation

The most common technology in use today is single-crystal PV, which uses wafers of silicon wired together and attached to a module substrate. Thin-film PV, such as amorphous silicon technology, uses silicon and other chemicals deposited directly on a substrate such as glass or flexible stainless steel. Thin films promise lower cost per unit area, but also have lower efficiency and produce less electricity per unit area compared to single-crystal PVs. Typical values for DC electrical power generation are around 6 W/ft^2 for thin film and up to 15 W/ft^2 for single-crystal PV.

PV panels produce direct current, not the alternating current used to power most building equipment. Direct current is easily stored in batteries; an inverter is required to transform the direct current to alternating current. The costs of an inverter and of reliable batteries to store electricity increase the overall cost of a system, which is usually $5 to $7/W (Krieth and Goswami 2007).

Another option is concentrated PV (CPV). CPV uses high-concentration lenses or mirrors to focus sunlight onto miniature solar cells. CPV systems must track the sun to keep the light focused on the PV cells. The main advantage of this system is higher efficiency than other technologies. Reliability, however, is an important technical challenge for this emerging technology: the systems generally require highly sophisticated tracking devices.

Being able to transfer excess electricity generated by a photovoltaic system back into the utility grid can be advantageous. Most utilities are required to buy excess site-generated electricity back from the customer. In many states, public utility commissions or state legislatures have mandated **netmetering**, which means that utilities pay and charge equal rates regardless of which way the electricity flows. A good source of rebates and incentives in the United States for solar systems and other renewable technologies is the Database of State Incentives for Renewable and Efficiency (DSIRE), available at www.dsireusa.org/ (North Carolina State University 2011). DSIRE is a comprehensive source of information on state, local, utility, and federal incentives and policies that promote renewable energy and energy efficiency, as well as state requirements for licensed solar contractors.

PV systems should be integrated during the early stages of the design. In existing facilities, a licensed contractor can be employed for a turnkey project, which includes sizing, analysis, economic analysis, design documents, specifications, permits, and documentation for incentives.

Available tools for analysis during design and installation of PV systems include the following:

- PVsyst, a PC software package for the study, sizing, simulation and data analysis of complete PV systems

(University of Geneva 2010) at www.pvsyst.com

- Hybrid Optimization Modeling Software (HOMER 2010), a program for analyzing and optimizing renewable energy technologies (www.homerenergy.com/)

- RETScreen (Natural Resources Canada 2010), a free decision support tool (which supports 35 languages) developed to help evaluate energy production and savings, costs, emission reductions, financial viability, and risk for various types of renewable energy technologies, at www.retscreen.net/ang/home.php

- eQUEST (Quick Energy Simulation Tool), a full-scale building energy simulation program capable of performing a complete building energy evaluation, at www.doe2.com/

Financing PV projects in the public sector can be more complex because of tax exemptions and efficient allocation of public funds and leverage incentives. The primary mechanism for financing public-sector PV projects is a third-party ownership model, which allows the public sector to take advantage of all the federal tax and other incentives without large up-front outlay of capital. The public sector does not own the solar PV, but only hosts it on its property. The cost of electrical power generated is then secured at a fixed rate, which is lower than the retail price for 15 to 25 years. Cory et al. (2008) discuss solar photovoltaic financing for the public sector in detail.

Solar/Thermal. Some commercial facilities can consider active thermal solar heating systems. Solar hot-water systems usually can reduce the energy required for service hot water. Solar heating design and installation information can be found in ASHRAE (1988, 1991). Chapter 37 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* and Krieth and Goswami (2007) are good sources of information for design and installation of active solar systems, as are Web-based sources such as U.S. Department of Energy's Energy Efficiency and Renewable Energy page at www.energy.gov/eere/renewables/solar.

Value Engineering and Life-Cycle Cost Analysis

Use of value engineering (VE) and life-cycle cost analysis (LCCA) studies is growing in all types of construction and as part of the integrated design process (IDP). VE and LCCA are logical, structured, systematic processes used as decision support tools to achieve overall cost reduction, but they are two distinct tools (Anderson et al. 2004).

Value engineering refers to a process where the project team examines the proposed design components in relation to the project objectives and requirements. The intent is to provide essential functions while exploring cost savings opportunities through modification or elimination of nonessential design elements. Examples are alternative systems, and substitute equipment. VE typically includes seven steps, as shown in Figure 11 of Chapter 8.

Life-cycle cost analysis is used as part of VE to evaluate design alternatives (e.g., alternative systems, equipment substitutions) that meet the facility design criteria with reduced cost or increased value over the life of the facility or system.

The combination of VE and LCCA is suitable for public facilities, which are often government funded and intended for longer lifespans than commercial facilities. Unfortunately, these tools often are not included in the early stages of the design, which results in a last-minute effort to reduce cost and stay within the budget, compromising issues such as energy efficiency and overall value of the facility. To avoid this, VE and LCCA should be deployed in the early stages of the project.

LCCA is recommended as part of any commercial building construction for economic evaluation. Chapters 37 and 58 discuss LCCA in detail. Other methodologies such as simple payback should be avoided because of inaccuracies and the need to take into account the time value of money. Life-cycle cost is more accurate because it captures all the major initial costs associated with each item, the costs occurring during the life of the system, and the value of money for the entire life of the system.

5. COMMISSIONING AND RETROCOMMISSIONING

Commissioning (Cx) is a quality assurance process for buildings from predesign through design, construction, and operations. It involves achieving, verifying, and documenting the performance of each system to meet the building operational needs. Given the growing demand for enhanced indoor air quality, thermal comfort, noise, etc., in commercial facilities and the application of equipment and systems such as DOAS, EMS, and occupancy sensors, it is important to follow the commissioning process as described in Chapter 44 and ASHRAE *Guideline* 0. The technical requirements for the commissioning process are described in detail in ASHRAE *Guideline* 1.1. Another source is ACG (2005). Proper commissioning ensures fully functional systems that can be operated and maintained properly throughout the life of the building. Although commissioning activities should be implemented by qualified commissioning professional [commissioning authority (CA)], it is important for other professionals to understand the basic definitions and processes in commissioning, such as the following:

- Owner project requirements (OPR), which is a written document that details the functional requirements of the project and the expectations of how it will be used and operated.

- Commissioning refers to a quality-focused process for enhancing the delivery of a project. The process focuses upon verifying and documenting that the facility and all its systems and assemblies are planned, installed, tested, and maintained to meet the OPR.
- Recommissioning is an application of the commissioning process to a project that has been delivered using the commissioning process.
- Retrocommissioning is applied to an existing facility that was not previously commissioned.
- Ongoing commissioning is a continuation of the commissioning process well into the occupancy and operation phase.

Commissioning: New Construction

Table 7 shows the phases of commissioning a new building, as defined by ASHRAE *Guideline* 1.1.
ACG (2005) refers to the following HVAC commissioning processes for new construction:

- Comprehensive HVAC commissioning starts at the inception of a building project from the predesign phase till postacceptance)
- Construction HVAC commissioning occurs during construction, acceptance, and postacceptance (predesign and design phases are not included in this process)

Commissioning is an important element in LEED for new construction (USGBC 2022). As a prerequisite (Energy and Atmosphere, prerequisite 1), commissioning must verify that the project's energy-related systems are installed and calibrated, and perform according to the OPR, BOD, and the construction document. Additional credits (Energy and Atmosphere, credit 3—Enhanced Commissioning) can be obtained by applying the entire commissioning process (or the comprehensive HVAC commissioning) as described previously.

Commissioning: Existing Buildings

HVAC commissioning in existing buildings covers the following:

- Recommissioning
- Retrocommissioning (RCx)
- HVAC systems modifications

Although the methodology for both is identical, there is a difference between recommissioning and retrocommissioning. Recommissioning is initiated by the building owner and seeks to resolve ongoing problems or to ensure that systems continue to meet the facility's requirements. There are can be changes in the building's occupancy or design strategies, outdated equipment, degraded equipment efficiency, occupant discomfort, and IAQ problems that can initiate the need for recommissioning. Typical recommissioning activities are shown in Table 8.

Table 7 Key Commissioning Activities for New Building

Phase	Key Commissioning Activities
Predesign	Preparatory phase in which the OPR is developed and defined.
Design	OPR is translated into construction documents, and basis of design (BOD) document is created to clearly convey assumptions and data used to develop the design solution. See informative annex k of ASHRAE *Guideline* 1.1-2007 for detailed structure and an example of a typical bod.
Construction	The commissioning team is involved to ensure that systems and assemblies installed and placed into service meet the OPR.
Occupancy and operation*	The commissioning team is involved to verify ongoing compliance with the OPR.

Source: ASHRAE *Guideline* 1.17.

* Also known as acceptance and post-acceptance in ACG (2005).

Table 8 Key Commissioning Activities for Existing Building

Phase	Key Commissioning Activities

Planning	Define HVAC goals
	Select a commissioning team
	Finalize recommissioning scope
	Documentation and site reviews
	Site survey
	Preparation of recommissioning plan
Implementation	Hire testing and balancing (TAB) agency and automatic temperature control (ATC) contractor
	Document and verify tab and controls results
	Functional performance tests
	Analyze results
	Review operation and maintenance (O&M) practices
	O&M instruction and documentation
	Complete commissioning report

Source: ACG (2005).

Commissioning is also an important element in existing buildings. USGBC (2022), *LEED v4.1: Operations + Maintenance* awards up to six credits for commissioning systems in existing buildings in the Energy and Atmosphere (EA) section.

HVAC systems modifications can vary from minor modification to HVAC systems up to complete reconstruction of all or part of building HVAC system. The process for this type of project should follow the process described previously for new construction.

6. SEISMIC AND WIND RESTRAINT CONSIDERATIONS

Seismic bracing of HVAC equipment should be considered. Wind restraint codes may also apply in areas where tornadoes and hurricanes necessitate additional bracing. This consideration is especially important if there is an agreement with local officials to use the facility as a disaster relief shelter. See Chapter 56 for further information.

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