Related Commercial Resources

CHAPTER 7

EDUCATIONAL FACILITIES

THIS chapter contains technical, environmental, and design considerations to assist the design engineer in the proper application of heating, ventilation, and air-conditioning systems and equipment for educational facilities.

1. PRESCHOOLS

General Design Considerations

Commercially operated preschools are generally provided with standard architectural layouts based on owner-furnished designs. A typical preschool facility provides programs for infants (1 to 2 years old), toddlers (2 years old), and preschoolers (3 to 4 years old). Larger facilities also offer programs for older children, such as kindergarten programs (5 years old). Areas such as lobbies, libraries, and kitchens are also included to support the variety of programs. Given this range of age, special attention for the design of the HVAC systems is required to meet the needs of every age group.

All preschool facilities require quiet and economical systems. The equipment should be easy to operate and maintain, and the design should provide warm floors and no drafts. These facilities have two distinct occupant zones: (1) the floor level, where younger children play, and (2) normal adult height, for the teachers. The teacher also requires a place for a desk; consider treating this area as a separate zone.

Preschool facilities generally operate on weekdays from early in the morning to 6:00 or 7:00 PM. This schedule usually coincides with the normal working hours of the children's parents plus one hour for drop-off and pick-up. The HVAC systems therefore operate 12 to 14 h per workday, and may be off or on at night and weekends, depending on whether setback is applied.

Supply air outlets should be positioned so that the floor area is maintained at about 24°C without introducing drafts. Both supply and return air outlets should be placed where they will not be blocked by furniture positioned along the walls or where children can reach them. Coordination with the architect about locating these outlets is essential. Proper ventilation is crucial for controlling odors and helping prevent the spread of diseases among the children.

Floor-mounted heating equipment, such as electric baseboards heaters, should be avoided because children must be prevented from coming in contact with hot surfaces or electrical devices. However, radiant-floor systems can be used safely and effectively.

Design Criteria

Table 1 provides typical indoor design conditions for preschools. Table 2 provides typical ventilation and exhaust design criteria using the ventilation rate procedure of ANSI/ASHRAE *Standard* 62.1-2013. Table 3 lists design criteria for acceptable noise in preschool facilities.

The preparation of this chapter is assigned to TC 9.7, Educational Facilities.

Table 1 Recommended Temperature and Humidity Design Criteria for Various Spaces in Preschools

Category/Humidity Criteria	Indoor Design Conditions, °C Winter	Summer
Infant, Toddler, and Preschooler Classrooms[a]		
30% rh	22.3 to 26.2	24.5 to 27.5
40% rh	22.3 to 25.8	24.3 to 27.2
50% rh	22.1 to 25.6	24.1 to 26.9
60% rh	21.87 to 25.3	23.8 to 26.7
Administrative, Offices, Lobby, Kitchen		
30 to 60% rh	22.3 to 25.3	24.5 to 26.7
Storage		
No humidity control	17.8	
Mechanical Rooms[b]		
No humidity control	16.1	

Notes:

[a] Based on *ASHRAE Thermal Comfort Tool* (ASHRAE 2010) v. 2.0.03, for people wearing typical summer and winter clothing, 0.6 and 0.9 clo, respectively, at sedentary activity (1.0 met). Air speed assumed at 0.1 m/s and mean radiant temperature (MRT) assumed equal to air temperature. Temperature range is within acceptable ASHRAE *Standard* 55 range (–0.5 < Predicted mean vote (PMV) < +0.5) using the analytical comfort zone method, section 5.3.2 of ASHRAE *Standard* 55-2013.

[b] Usually not conditioned.

Load Characteristics

Preschool cooling and heating loads depend heavily on ambient conditions, because the rooms typically have exterior exposures (walls, windows, and roofs) and also relatively higher needs for ventilation. Although preschool facilities are relatively small, the design engineer must pay special attention to properly calculate the cooling, heating, dehumidification, and humidification loads. Sizing and applying the HVAC equipment is critical for handling the loads and the large amounts of outdoor air from a capacity and occurrence standpoint (peak sensible and latent loads do not always coincide).

Humidity Control

Preschool classrooms require humidity control to provide human comfort and prevent health problems. Maintaining humidity levels between –1 and 15.5°C dew point satisfies nearly all people nearly all the time. However, the designer should discuss comfort expectations with the owner, to avoid misunderstandings.

In hot and humid climates, it is recommended that air conditioning and/or dehumidification be operated year-round to prevent growth of mold and mildew. Dehumidification can be improved by adding optional condenser heat/reheat coils, heat pipes, or air-to-air heat exchangers in conjunction with humidity sensors in the conditioned space or return air.

Additional information on humidity control is in the section on K-12 Schools.

Systems and Equipment Selection

HVAC systems for preschools are typically decentralized, using either self-contained or split air-conditioners or heat pumps (typically

Table 2 Typical Recommended Design Criteria for Ventilation and Filtration for Preschools

	Ventilation and Exhaust [a, g, j]				
			Outdoor Air		
Category	Outdoor Air, L/s per Person	Occupant Density [k] per 100 m²	L/(s·m²)	L/s per Unit	Minimum Filtration Efficiency, MERV [h]
Infant, Toddler, and Preschooler Classrooms[b]	8.6	25			6 to 8
Administrative and Office Space[c]	8.5	5			6 to 8
Kitchen[d]			1.5 (exhaust)		i
Toilets[e]				25 (exhaust)	NA
Storage[f]			0.6		1 to 4

Notes:

[a] Based on ANSI/ASHRAE *Standard* 62.1-2013, Table 6.2.2.1, default values for ventilation, and Table 6-5 for exhaust rates.

[b] Based on ASHRAE *Standard* 62.1-2013, Table 6.2.2.1, default values for educational facilities-daycare.

[c] Based on ASHRAE *Standard* 62.1-2013, Table 6.2.2.1, default values for office buildings/office spaces.

[d] Based on ASHRAE *Standard* 62.1-2013, Table 6.5, for kitchenettes.

[e] Based on ASHRAE *Standard* 62.1-2013, Table 6.5, for private toilets (rate is for toilet room intended to be occupied by one person).

[f] Based on ASHRAE *Standard* 62.1-2013, Table 6.2.2.1, for storage rooms.

[g] This table should not be used as the only source for design criteria. Governing local codes, design guidelines, and ASHRAE *Standard* 62.1-2013 with current addenda *must* be consulted.

[h] MERV = minimum efficiency reporting values, based on ASHRAE *Standard* 52.2-2012.

[i] See Chapter 31 for additional information on kitchen ventilation.

[j] Consult local codes for exhaust requirements.

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

Table 3 Typical Recommended Design Guidelines for HVAC-Related Background Sound for Preschool Facilities

	Sound Criteria [a, b]	
Category	NC/RC	Comments
Infant, Toddler, and Preschooler Classrooms	30	
Administrative/Office Areas	40	For open-plan office
Service/Support Areas	35 to 45	

Notes:

[a] Based on Chapter 48.

[b] RC (Room Criterion), from Chapter 8 of 2013 *ASHRAE Handbook—Fundamentals*.

Table 4 Applicability of Systems to Typical Areas[d]

	Decentralized Cooling/Heating Systems[c]				Heating Only
Typical Area	PSZ/ SZ Split	PSZ with Energy Recovery and Dehumidification	WSHP	Geothermal Heat Pump	Radiant Floor [b]
Classrooms	X[a]	X[a]	X	X	X
Administrative Areas, Lobby	X		X	X	
Kitchen	X		X	X	
Ventilation (Outdoor Air)	DOAS		DOAS	DOAS	DOAS

SZ = single zone
PSZ = packaged single zone
WSHP = water-source heat pump
DOAS = dedicated outdoor air system

Notes:

[a] PSZ for classrooms requires individual thermostatic control.

[b] Typically with cooling system such as PSZ/SZ split.

[c] Heating system for PSZ/SZ split can be gas furnace, hot-water coil, or electric.

[d] See Table 10 for additional systems if preschool is not a stand-alone facility.

air- or water-source). When the preschool is part of a larger facility, utilities such as chilled water, hot water, or steam from a central plant can be used. When natural gas is available, the heating system can be a gas-fired furnace, or, when economically justifiable, electric heat can be used.

The type of HVAC equipment selected also depends on the climate and the months of operation. In hot and dry climates, for instance, the primary type of cooling may be evaporative. In colder climates, heating can also be provided by a hot-water hydronic system originating from a boiler plant in conjunction with radiant floor or hot-water coils. For small, decentralized systems without central building control, a zone-level programmable temperature control is recommended (if not required by local code).

Decentralized systems are dedicated systems serving a single zone, and typically include the following:

- Direct-expansion (DX) split systems
- Rooftop packaged air conditioners or heat pumps with or without optional enhanced dehumidification (condenser reheat coil)
- Rooftop packaged air conditioners or heat pumps integrated with an energy recovery module, with optional enhanced dehumidification (condenser reheat coil; see Figure 5). Consult ANSI/ASHRAE/IESNA *Standard* 90.1-2013, section 6.5.6.1, for cases with a high percentage of outdoor air.
- Water-source heat pumps (with cooling tower and supplementary boiler)
- Geothermal heat pumps (ground-coupled, ground-water-source, surface-water-source)
- Packaged dedicated outdoor air systems with DX system for cooling and gas-fired furnace, electric heating, or part of water-source and geothermal heat pump system

Information about decentralized systems can be found in Chapters 5, 18, 49, and 50 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment*. Additional information on geothermal heat pumps can be found in Kavanaugh and Rafferty (1997) and Chapter 34 of this volume. Chapter 6 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment* provides information on radiant heating.

Note that some decentralized systems may need additional acoustical modifications to meet the design criteria in Table 3. Therefore, it is strongly recommended to carefully check the acoustical implications of applying these systems.

Dedicated Outdoor Air Systems (DOASs). Specialized DOASs should be used to treat outdoor air before it is introduced into classrooms or other areas. DOAS units can bring 100% outdoor air to at least space conditions, which allows the individual space units to handle only the space cooling and heating loads. A detailed description of DOAS is provided in the K-12 Schools section of this chapter. Additional information can be found in Chapter 25 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment*.

Systems Selection by Application. Table 4 shows the applicability of systems to areas in preschool facilities.

2. K-12 SCHOOLS

General and Design Considerations

K (kindergarten)-12 schools typically include elementary, middle (or junior high), and high schools. These facilities are typically one- to three-story buildings.

Elementary schools are generally comprised of 10 to 15 classrooms plus cafeteria, administration, gymnasium, and library areas. Elementary schools are typically used during the school season (late August to June); during summer, they are typically closed or have minimal activity. Current trends include science classrooms and a

Table 5 Typical Spaces in K-12 Schools

	School		
Typical Area	Elementary (K to 5)[a]	Middle (6 to 8)[a]	High (9 to 12)[a]
Classrooms	X	X	X
Science	X	X	X
Computer	X	X	X
Laboratories and Science Facilities		X	X
Administrative Areas	X	X	X
Gymnasium	X	X	X
Libraries	X	X	X
Auditorium			X
Home Economics Room			X
Cafeteria	X	X	X
Kitchen	X	X	X
Auto Repair Shop[b]			X
Industrial Shop			X
Locker Rooms		X	X
Ice Rink[b]			X
Natatorium[b]			X
School Store[b]			X

Notes: [a]School grades can vary. [b]These zones are not typical.

preschool facility. Typical elementary schools operate between 7:00 AM and 4:00 PM.

Middle schools are larger than elementary schools and include additional computer classrooms and locker rooms. Their hours of operation are longer because of extracurricular activities. A recent trend toward eliminating middle schools (retaining traditional K-8 elementary and 9-12 high schools) (Wright 2003) may require that elementary school designs incorporate some middle school features.

High schools also include a cafeteria and auditorium, and may include a natatorium, ice-skating rink, etc. High schools operate longer hours and are often open during the summer, either as a summer school or to use special facilities such as gymnasiums, natatoriums, etc.

Typical areas found in K-12 schools are shown in Table 5.

K-12 schools require an efficiently controlled atmosphere for a proper learning environment. This involves the selection of HVAC systems, equipment, and controls to provide adequate ventilation and indoor air quality (IAQ), comfort, and a quiet atmosphere. The system must also be easily maintained by the facility's maintenance staff.

The following are general design considerations for each of the areas typically found in K-12 schools:

Classrooms. Classrooms typically range between 80 and 100 m^2, and are typically designed for 20 to 30 students. Each classroom should be, at a minimum, heated and ventilated. Air conditioning should be seriously considered for school districts that have year-round classes in warm, humid climates. In humid climates, seriously consider providing dehumidification during summer, even if the school is unoccupied, to prevent mold and mildew.

Science Classrooms. Science rooms are now being provided for elementary schools. Although the children do not usually perform experiments, odors may be generated if the teacher demonstrates an experiment or if animals are kept in the classroom. Under these conditions, adequate ventilation is essential along with an exhaust fan with a local, timer-based (e.g., 0 to 60 min) on/off switch for occasional removal of excessive odors.

Computer Classrooms. These rooms have a high sensible heat load because of the computer equipment. They may require additional cooling equipment such as small spot-cooling units to offset the additional load. Humidification may also be required. See Chapter 19 for additional information.

Educational Laboratories. Middle and high school laboratories and science facilities may require fume hoods with special exhaust systems. A makeup air system may be required if there are several fume hoods in a room. If there are no fume hoods, a room exhaust system is recommended for odor removal, depending on the type of experiments conducted in the room and whether animals are kept there; when applicable, a local exhaust with on/off switch and a timer can be considered. Associated storage and preparation rooms are generally exhausted continuously to remove odors and vapors emanating from stored materials. The amount of exhaust and location of exhaust grilles may be dictated by local codes or National Fire Protection Association (NFPA) standards. See Chapter 16 for further information. Additional information on laboratories can be found in ANSI/AIHA *Standard* Z9.5-2012 and McIntosh et al. (2001).

Administrative Areas. The office area should be set up for individual control because it is usually occupied during and after school hours. Because offices are also occupied before school starts in the fall, air conditioning for the area should be considered or provisions should be allowed for future upgrades.

Gymnasiums. Gyms may be used after regular school hours for evening classes, meetings, and other functions. The gym may also be used on weekends for group activities. Loads for these occasional uses should be considered when selecting and sizing the systems and equipment. Independent gymnasium HVAC systems with control capability allow for flexibility with smaller part-load conditions. If a wooden floor is installed, humidity control should be considered to avoid costly damage.

Libraries. Libraries should be air conditioned to preserve the books and materials stored in them. See Chapters 3 and 23 for additional information.

Auditoriums. These facilities require a quiet atmosphere as well as heating, ventilation, and, in some cases, air conditioning. Auditoriums are not often used, except for assemblies, practice for programs, and special events. For other considerations, see Chapter 5.

Home Economics Rooms. These rooms usually have a high sensible heat load from appliances such as washing machines, dryers, stoves, ovens, and sewing machines. Different options should be considered for exhaust of stoves and dryers. If local codes allow, residential-style range hoods may be installed over the stoves. A central exhaust system could be applied to the dryers as well as to the stoves. If enough appliances are located within the room, a makeup air system may be required. These areas should be maintained at negative pressure in relation to adjacent classrooms and administrative areas. See Chapter 33 for more information.

Cafeteria and Kitchen. Typical schools require space for preparation and serving of meals. A well-designed school cafeteria includes the following areas: loading/receiving, storage, kitchen, serving area, dining area, dishwashing, office, and staff facilities (lockers, lavatories, and toilets). Chapter 33 provides detailed information on design criteria, load characteristics, and design concepts for these facilities.

Auto Repair Shops. These facilities require outdoor air ventilation to remove odors and fumes and to provide makeup air for exhaust systems. The shop is usually heated and ventilated but not air conditioned. To contain odors and fumes, return air should not be supplied to other spaces, and the shop should be kept at a negative pressure relative to surrounding spaces. Special exhaust systems such as welding exhaust or direct-connected carbon monoxide exhaust systems may be required. See Chapter 32 for more information.

Industrial Shops. These facilities are similar to auto repair shops and have special exhaust requirements for welding, soldering, and paint booths. In addition, a dust collection system is sometimes provided and the collected air is returned to the space. Industrial shops have a high sensible load from operation of the shop equipment. When calculating loads, the design engineer should consult the teacher about shop operation, and, where possible, diversity factors should be applied. See Chapter 32 for more information.

Locker Rooms. Building codes in the United States require that these facilities be exhausted directly to the outside when they contain toilets and/or showers. They are usually heated and ventilated only. These areas typically require makeup air and exhaust systems that should operate only when required. Where applicable, energy recovery systems can be considered.

Ice Rinks. These facilities require special HVAC and dehumidification systems to keep spectators comfortable, and to prevent roof condensation and fog formation at the surface. Where applicable, energy recovery systems can be considered. See Chapter 5 of this volume, Chapter 44 of the 2014 *ASHRAE Handbook—Refrigeration*, and Harriman et al. (2001) for more on these systems.

Natatoriums. These facilities, like ice rinks, require special humidity control systems. In addition, special construction materials are required. Where applicable, energy recovery systems can be considered. See Chapter 5 and Harriman et al. (2001) for more on these systems.

School Stores. These facilities contain school supplies and paraphernalia and are usually open for short periods. The heating and air-conditioning systems serving these areas should be able to be shut off when the store is closed to save energy.

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 covered by ANSI/ASHRAE *Standard* 55-2013 and Chapter 9 of the 2013 *ASHRAE Handbook—Fundamentals*. Ventilation and IAQ are covered by ANSI/ASHRAE *Standard* 62.1-2013 and Chapter 16 of the 2013 *ASHRAE Handbook—Fundamentals*. Sound and vibration are discussed in Chapter 48 of this volume and Chapter 8 of the 2013 *ASHRAE Handbook—Fundamentals.*

Thermal comfort is affected by air temperature, humidity, air velocity, and mean radiant temperature (MRT). In addition, nonenvironmental factors (clothing, gender, age, and physical activity) affect thermal comfort. These variables and their correlation with thermal comfort can be evaluated by the *Thermal Comfort Tool CD* (ASHRAE 2010) in conjunction with ANSI/ASHRAE *Standard* 55-2013. Note that, in addition to thermal comfort criteria, several zones in schools (libraries, gymnasiums, locker rooms, natatoriums, ice rinks, etc.) require additional considerations to cover issues such as mold prevention, condensation, corrosion, etc., as discussed in more detail in the section on Humidity Control. General guidelines for temperature and humidity applicable for K-12 schools are shown in Table 6.

All schools 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. ANSI/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 7 provides recommendations for ventilation design based on the ventilation rate procedure method of ANSI/ASHRAE *Standard* 62.1-2013 and filtration criteria for K-12 educational facilities.

Additional information on IAQ for educational facilities can be found in EPA (2000).

Table 6 Typical Recommended Temperature and Humidity Ranges for K-12 Schools

Category/ Humidity Criteria	Indoor Design Conditions: Temperature, °C Winter	Summer	Comments
Classrooms, Laboratories, Libraries, Auditoriums, Offices[a, e]			
30% rh	22.3 to 26.2	24.5 to 27.5	
40% rh	22.3 to 25.8	24.3 to 27.2	
50% rh	22.1 to 25.6	24.1 to 26.9	
60% rh	21.87 to 25.3	23.8 to 26.7	
Gymnasiums			
30 to 60% rh	20.3 to 23.3	23.3 to 25.8	For gym with wooden floor, 35 to 50% humidity recommended at all times
Shops			
20 to 60% rh	20.3 to 23.3	23.3 to 25.8	
Cafeteria[b]			
20 to 30% (winter), 50% (summer) rh	21.1 to 23.3	25.8	
Kitchen[b]			
No humidity control	21.1 to 23.3	28.9 to 31.1	
Locker/Shower Rooms			
No humidity control	26.7		Usually not conditioned
Toilets			
No humidity control	22.2		Usually not conditioned
Storage			
No humidity control	17.8		
Mechanical Rooms			
No humidity control	16.1		Usually not conditioned
Corridors			
No humidity control	20.0		Frequently not conditioned
Natatorium[c]			
50 to 60% rh	26.7 to 28.9	26.7 to 28.9	Based on recreational pool
Ice Rink[d]			
1.7 to 7.2°C dp (maximum)	10.0 (minimum)	18.3 (maximum)	Minimum 5.5 K temperature difference between dew point and dry bulb to prevent fog and condensation

Notes:

[a] Based on *ASHRAE Thermal Comfort Tool* v. 2.0.03, for people wearing typical summer and winter clothing, 0.6 and 0.9 clo respectively, at sedentary activity (1.0 met). Air speed assumed at 0.1 m/s and MRT assumed equal to air temperature. The temperature range is within acceptable ASHRAE *Standard* 55 range (–0.5< PMV<+0.5) using the analytical comfort zone method, section 5.3.2 of ASHRAE *Standard* 55-2013.

[b] Based on Chapter 3.

[c] Based on Chapter 5.

[d] Based on Harriman et al. (2001).

[e] For libraries, keep minimum humidity of –1.1°C dp and maximum of 55% rh.

Acceptable noise levels in classrooms are critical for a proper learning environment. High noise levels reduce speech intelligibility and student's learning capability. Although Chapter 48 provides information on design noise criteria, additional sources, such as local codes and ANSI *Standard* S12.60-2010 Part 1, should be consulted for adequate design criteria. Table 8 summarizes applicable noise criteria for K-12 schools.

Load Characteristics

Proper cooling, heating, dehumidification, and humidification load calculations and properly sized equipment are critical to both energy efficiency and cost effectiveness. Many computer programs

Table 7 Typical Recommended Design Criteria for Ventilation and Filtration for K-12 Schools

	Ventilation and Exhaust[a]				
Category	Combined Outdoor Air, L/s per Person	Occupant Density,[i] per 100 m^2	Outdoor Air		Minimum Filtration Efficiency, MERV[c]
			$L/(s\cdot m^2)$	L/s per Unit	
Classrooms, Ages 5 to 8	7.4	25			6 to 8
Ages 9 and over	6.7	35			6 to 8
Lecture	4.3	65			6 to 8
Art	9.5	20			6 to 8
Lecture Halls (fixed seats)	4.0	150			6 to 8
Science Laboratories[f]	8.6	25			6 to 8
Computer Lab	7.4	25			6 to 8
Media Center	7.4	25			6 to 8
Music/Theatre/ Dance	5.9	35			6 to 8
Multiuse Assembly	4.1	100			6 to 8
Libraries	8.5	10			6 to 8
Auditorium	2.7	150			9 to 10[g]
Administrative/ Office Areas	8.5	5			6 to 8
Gymnasium (playing floors)			1.5		6 to 8
Wood/Metal Shops	9.5	20			6 to 8
Locker Rooms			2.5 (exhaust)		1 to 4
Cafeteria	4.7	100			6 to 8
Kitchen[d, e]			3.5 (exhaust)		NA
Toilets				35 (exhaust)	NA
Storage			0.6		1 to 4
Corridors			0.3		6 to 8
Natatoriums (pool and deck)			2.4		6 to 8
Ice Rinks (spectator areas)[h]	4.0	150			6 to 8

Notes:

[a] Based on ANSI/ASHRAE *Standard* 62.1-2013, Tables 6.2.2.1 (i.e., default values) and 6-4. For systems serving multiple zones, apply multiple-zone calculations procedure. See the section on Demand Control Ventilation (DCV) when DCV is considered.

[b] This table should not be used as the only source for design criteria. Governing local codes, design guidelines, and ANSI/ASHRAE *Standard* 62.1-2013 *must* be consulted.

[c] MERV = minimum efficiency reporting values, based on ASHRAE *Standard* 52.2-2012.

[d] See Chapter 33 for additional information on kitchen ventilation.

[e] Consult local codes for kitchen exhaust requirements.

[f] This table should not be used as the only source for laboratory design criteria. Governing local codes and design guidelines such as ANSI/AIHA *Standard* Z9.5-2012 and Chapter 16 of this volume *must* be consulted.

[g] When higher filtration efficiency specified, prefiltration is recommended.

[h] Based on ANSI/ASHRAE *Standard* 62.1-2013 values for sports and entertainment; for rink playing area, use gymnasium (playing floors) design criteria. Special attention should be given to internal-combustion ice-surfacing equipment for carbon monoxide control. Consult local code for ice rink design.

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

Table 8 Typical Recommended Design Guidelines for HVAC-Related Background Sound for K-12 Schools

Category	Sound Criteria[a, b] NC/RC	Comments
Classrooms	30	
Large Lecture Rooms Without Speech Amplification	25	
Large Lecture Rooms with Speech Amplification	30	
Science Laboratories	35 to 50	See Table 1 of Chapter 48
Libraries	30	See Table 1 of Chapter 48
Auditorium	30 to 35	Use as guide only; consult acoustician
Administrative	40	For open-office space
Gymnasium	45	
Shops	35 to 45	Use as guide only; consult acoustician
Cafeteria	40	Based on service/ support for hotels
Kitchen	40	Based on service/ support for hotels
Storage	35 to 45	Use as guide only; consult acoustician
Mechanical Rooms	35 to 45	Use as guide only; consult acoustician
Corridors	40	
Natatoriums	45	
Ice Rinks	45	Based on values for gymnasiums and natatoriums

Notes:

[a] Based on Chapter 48, Table 1. That table provides additional design guidelines for HVAC-related background sound in rooms.

[b] RC (Room Criterion), from Chapter 7 of the 2013 *ASHRAE Handbook—Fundamentals*.

and calculation methodologies, as described in Chapter 18 of the 2013 *ASHRAE Handbook—Fundamentals*, can be used for these tasks. Assumptions and data used about infiltration, lighting, equipment loads, occupancy, etc., are critical for proper load calculations. Although equipment is sized by peak cooling and heating, it is extremely important to analyze the occurrences of the peak sensible and latent cooling loads. In many instances, peak sensible cooling load does not coincide with peak latent cooling load. Ignoring this phenomenon can result in unacceptable indoor humidity. By carefully analyzing and understanding the peak loads and the load profiles, the designer can properly apply and size the most suitable equipment to meet the sensible and the latent cooling loads efficiently. Elementary schools are generally occupied from about 7:00 AM to about 3:00 PM; occupation is longer for middle and high schools. Peak cooling loads usually occur at the end of the school day. Peak heating usually occurs early in the day, when classrooms begin to be occupied and outdoor air is introduced into the facility. Although K-12 schools are dominated by perimeter zones (and zones exposed to the roof), careful attention should be given to components of the loads. Typical breakdowns of moisture loads are shown in Table 9.

Typically, the dominant cooling loads in classrooms are occupants and ventilation, and ventilation and roof for heating. Given the dominance of ventilation loads, special effort should be made to effectively treat outdoor air before its introduction to the space, as discussed in more detail in the section on Systems and Equipment Selection.

Table 9 Typical Classroom Summer Latent (Moisture) Loads

Category	Moisture Loads, kg/h	Moisture Loads, %
People	3.3	22.5
Permeance	0.09	0.6
Ventilation	9.2	62.5
Infiltration	2.1	14.4
Doors	0	0
Wet Surfaces	0	0
Humid Materials	0	0
Domestic Loads	0	0

Note: Based on Harriman et al. (2001), Chapter 18, Figure 18.2.

Humidity Control

School buildings host many activities that require special humidity control. Harriman et al. (2001) provide detailed information on the basics of design and equipment selection for proper humidity control for several applications; Chapter 18 of that volume is dedicated to schools.

Classrooms require humidity control to provide comfort and prevent humidity-related problems (e.g., growth of dust mites and fungus, which produce allergens and even toxic by-products). Low humidity, on the other hand, favors longevity of infectious viruses, and therefore their transmission between occupants. Maintaining dew-point levels between –1 and 15.5°C satisfies nearly all people nearly all the time. However, the designer should discuss comfort expectations with the owner, to avoid misunderstandings.

Libraries require humidity control to provide human comfort to the occupants and also to protect books and electronic records. Maintaining dew-point levels between –1 and 15.5°C provides a comfortable environment for the library occupants. However, controlling humidity at this range does not prevent books from absorbing excess moisture. Typically, books take up moisture quickly but lose it slowly. To avoid growth of mold and mildew, a dew point above –1°C and maximum of 55% rh are recommended. As for classrooms, the principal moisture loads for the library are ventilation (the major load) and infiltration.

Gymnasiums with wooden floors require special attention; failure to control humidity in gyms with wooden floors may have costly consequences. The Maple Flooring Manufacturers Association (MFMA) specifies a floor-level humidity between 35 and 50% rh.

Showers and locker rooms require humidity control to prevent corrosion and growth of bacteria and fungus. Therefore, special attention is required to exhaust air quantities and placement of supply and exhaust air registers.

Natatoriums and ice rinks are typically isolated areas with more specialized HVAC equipment specifically designed to address ventilation and humidity control. Chapters 27 and 28 of Harriman et al. (2001) provide detailed information on humidity control for natatoriums and ice rinks, respectively.

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 the assumptions in the energy analysis with the school administration. Assumptions, especially about hard-to-measure items such as infiltration and part-load factors, can significantly affect the energy use calculated.

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) the age and condition of the existing equipment, pipes, and controls; and (3) the capital and operating costs of new equipment. Schools usually have very limited budgets. Any savings in capital expenditures and energy costs may be available for the maintenance and upkeep of the HVAC systems and equipment and for other facility needs.

The type of HVAC equipment selected also depends on the climate and months of operations. In hot, dry climates, for instance, evaporative cooling may be the primary approach. Some school districts may choose not to provide air conditioning. However, in hot, humid climates, it is recommended that air conditioning or dehumidification be operated year-round to prevent growth of mold or mildew.

Chapter 1 of the 2012 *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 (2015a, 2015b), can also be used for the LCC analysis along with software such as BLCC 5.1 (FEMP 2010). Refer to Chapters 37 and 58, and the Value Engineering (VE) and Life-Cycle Cost Analysis (LCCA) section of this chapter, for additional information.

System Types. HVAC systems for K-12 schools 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 2012 *ASHRAE Handbook—HVAC Systems and Equipment*)
- In-room terminal systems (see Chapter 5 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment*)
- DOAS with chilled water for cooling and hot water, steam, or electric heat for heating

Primary Systems

- Central cooling and heating plant (see Chapter 3 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment*)

Typical decentralized systems (dedicated systems serving a single zone, or packaged systems such as packaged variable-air-volume) are

- Water-source heat pumps (WSHPs), also known as water-loop heat pumps (WLHPs)
- Geothermal heat pumps (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, 18, 49, and 50 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment* provide additional information on decentralized HVAC systems. Additional information on geothermal energy can be found in Chapter 34 of this volume.

It is important to note that, to meet the acoustical design criteria in Table 8, designers should avoid locating HVAC equipment in classrooms, and that some centralized and decentralized systems located close to classrooms might need additional sound-attenuating features. Coordination between the HVAC designer, architect, and acoustical consultant is critical for meeting the desired noise criteria. Siebein and Likendey (2004) provide information on the applicability of systems to classrooms with regard to acoustical criteria. Additional information on how HVAC&R manufacturers' acoustical data and application information can be best used can be found in Ebbing and Blazier (1998). Schaffer (1993) provides a practical guide to noise and vibration control for HVAC systems. Commercial acoustics analysis software can also be helpful.

Dedicated Outdoor Air Systems. Although most centralized and decentralized systems are very effective at handling the space sensible cooling and heating loads, they are less effective (or ineffective) at handling ventilation air and the latent loads. As a result, a DOAS should be used. DOAS units bring 100% outdoor air to at least space conditions, which allows individual space units to handle only the space loads. It is preferable, however, to introduce the outdoor air at a lower humidity ratio than the desired space humidity ratio, to allow the zone HVAC unit to handle only the space sensible cooling load. This approach can be easily implemented in a classroom where a significant amount of outdoor air is required for ventilation.

Example. In a typical classroom with 30 students, the ventilation requirements are 222 L/s. If the outdoor air can be introduced at a humidity ratio of 6.9 g/kg and the space is designed to be maintained at 10 g/kg, the space dehumidification capability of the pre-dehumidified outdoor air is the following:

$$\begin{matrix}\text{Space dehumidification}\\ \text{capability, W}\end{matrix} = \begin{matrix}\text{Latent load}\\ \text{factor,}\\ \text{W/(L}\cdot\text{s)}\end{matrix} \times \begin{matrix}\text{Flow}\\ \text{rate,}\\ \text{L/s}\end{matrix} \times \left(\begin{matrix}\text{Space humidity ratio} -\\ \text{Supply humidity ratio}\end{matrix}\right)$$

Then,

$$\begin{matrix}\text{Dehumidification}\\ \text{capability, W}\end{matrix} = 3010 \times 222\left[\frac{(10-6.9)}{1000}\right] = 2071\text{ W} = 2.07\text{ kW}$$

where 3010 is the air latent factor (see Chapter 18 of the 2013 *ASHRAE Handbook—Fundamentals*), in W/(L·s).

The 2.07 kW of space latent load is equivalent to the latent load of 30 occupants (seated, very light work, 0.045 kW per occupant) and the additional space latent load (e.g., infiltration latent load).

Occupant latent load = 30 × 0.045 = 1.35 kW

$$\begin{matrix}\text{Remainder of total}\\ \text{dehumidification}\\ \text{capability}\end{matrix} = 2.07 - 1.35 = 0.72\text{ kW}$$

This additional dehumidification capability can help in handling infiltration latent load and others.

This simple example demonstrates the ability of pre-dehumidified outdoor air to handle the space latent load, resulting in almost full separation of the space latent cooling load treatment from the space sensible cooling load. This approach allows only thermostatic control without losing humidity control in conditioned classrooms.

Typical DOAS units are air-handling units that cool, dehumidify, heat, humidify, and filter the outdoor air before it is introduced to the conditioned space. Typical DOASs include the following major components:

- Mechanical cooling/dehumidification
  - DX coil
  - Chilled-water coil
- Desiccant-based cooling/dehumidification
  - Desiccant (dehumidification) and direct-expansion (DX) coil (post sensible cooling)
  - Desiccant (dehumidification) and chilled-water coil (post sensible cooling)
- Heating
  - Coils (hot-water, steam, electric, heat pump)
  - Gas-fired furnace
- Humidification
  - Passive (in conjunction with enthalpy wheel heat recovery)
  - Active (steam, electric-to-steam, gas-to-steam)
- Exhaust air recovery: air-to-air heat recovery
  - Rotary (enthalpy wheel, sensible wheel)
  - Fixed (heat pipe, plate heat exchanger, runaround coils)
- Dehumidification enhancements for air-to-air heat recovery
  - Heat pipe based (wraparound coil)
  - Mini plate heat exchanger based

Which DOAS configuration is most cost-effective depends on variables such as availability of utilities (chilled water, gas, steam), space constraints, climatic data, utility cost, and budget. DOAS can be configured easily by using modular components that meet the design criteria. Selection and analysis software of these systems is readily available from DOAS manufacturers, which simplifies configuration and analysis of the most cost-effective system. Typical configurations of DOAS are shown in Figures 1 and 2. A cooling/dehumidification psychrometrics process of DOAS shown in Figure 3.

Air-to-air energy recovery is an important element in a DOAS. In addition to recovering energy from the exhaust air, a well-designed energy recovery module, such as an enthalpy wheel, can enhance and stabilize operation of the cooling and heating elements in the

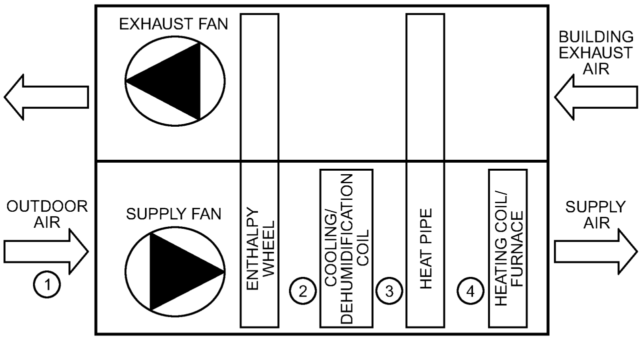


Fig. 1 Typical Configuration of DOAS Air-Handling Unit: Enthalpy Wheel with Heat Pipe for Reheat

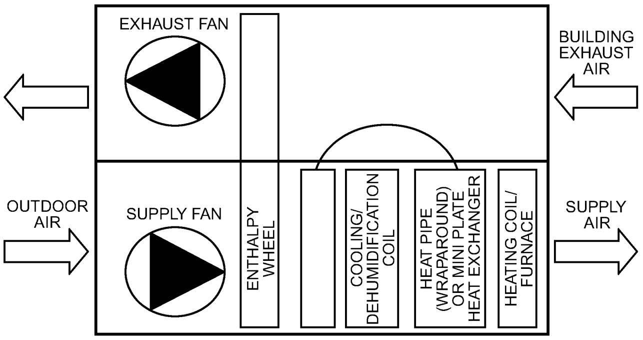


Fig. 2 Typical Configuration of DOAS Air-Handling Unit: Enthalpy Wheel with Wraparound Heat Pipe for Reheat

DOAS unit. As shown in Figure 3, the process of bringing outside air from point 1 to point 2 can be defined as "compressing" the outdoor air conditions to almost return air conditions.

Given the need for more stringent and complex control schemes for outdoor air preconditioning, DOAS typically incorporate, direct digital control (DDC) systems, either stand-alone microprocessor-based or with the ability to communicate with central energy management system. The control system can be purchased as an option or installed in the field by the controls vendor. Typical supply air conditions for a DOAS air-handling unit are shown in Table 10.

Typical arrangements of DOAS integrated with local cooling and heating systems are shown in Figure 4. Additional information on DOAS systems can be found in Chapter 25 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment*.

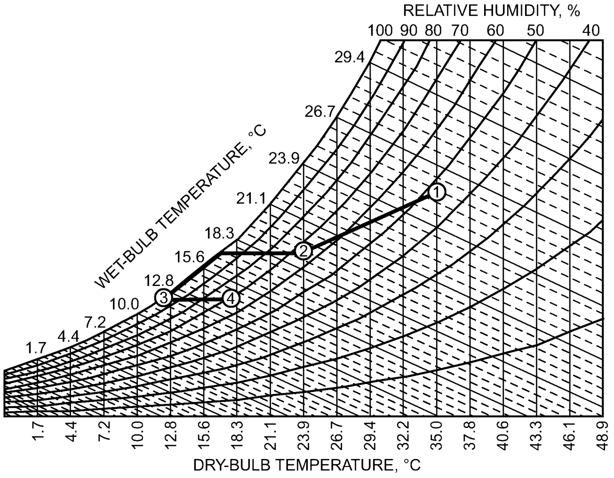


Fig. 3 Cooling/Dehumidification Psychrometric Process of Typical DOAS Air-Handling Unit in Figure 1

Systems with High Percentage of Outdoor Air. Air-handling systems with a high percentage of outdoor air (above 30%) can be found in several areas in educational facilities. To prevent indoor air quality problems and conserve energy, an energy recovery module can be added to pretreat the outdoor air before it is mixed with return air. Figure 5 shows a typical rooftop packaged AC unit with energy recovery module. See Chapter 26 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment* for more information on energy recovery equipment and systems.

The addition of an energy recovery module is dependent on the percentage of outdoor air and the geographic location. See ANSI/ASHRAE/IES *Standard* 90.1-2013, section 6.5.6.1, for the correlation between geographic location and percentage of outdoor air (OA). It is strongly recommended to check the exceptions listed in that section.

Systems Selection by Application. Table 11 shows the applicability of systems to areas in K-12 school facilities.

Displacement Ventilation and Active/Induction Chilled Beams

Displacement Ventilation. The use of displacement ventilation (as opposed to the more traditional mixing ventilation) for classrooms has been extended for enhanced IAQ and thermal comfort. In displacement ventilation, fresh air at colder temperature than the room air is discharged close to the floor level, and warm air is

Table 10 Typical Design Criteria for DOAS Air-Handling Unit

	Supply Air Conditions[a]		Minimum Air Filtration Efficiency, MERV[b]
	Temperature, °C	Humidity Ratio, g/kg	
Winter	18 to 20	4 to 6	6 to 8
Summer	15 to 18	6 to 9	6 to 8

Notes:
[a] Building location may dictate optimum supply condition in recommended range.
[b] Filter efficiency definition per ASHRAE *Standard* 52.2-2012.
MERV = minimum efficiency reporting values

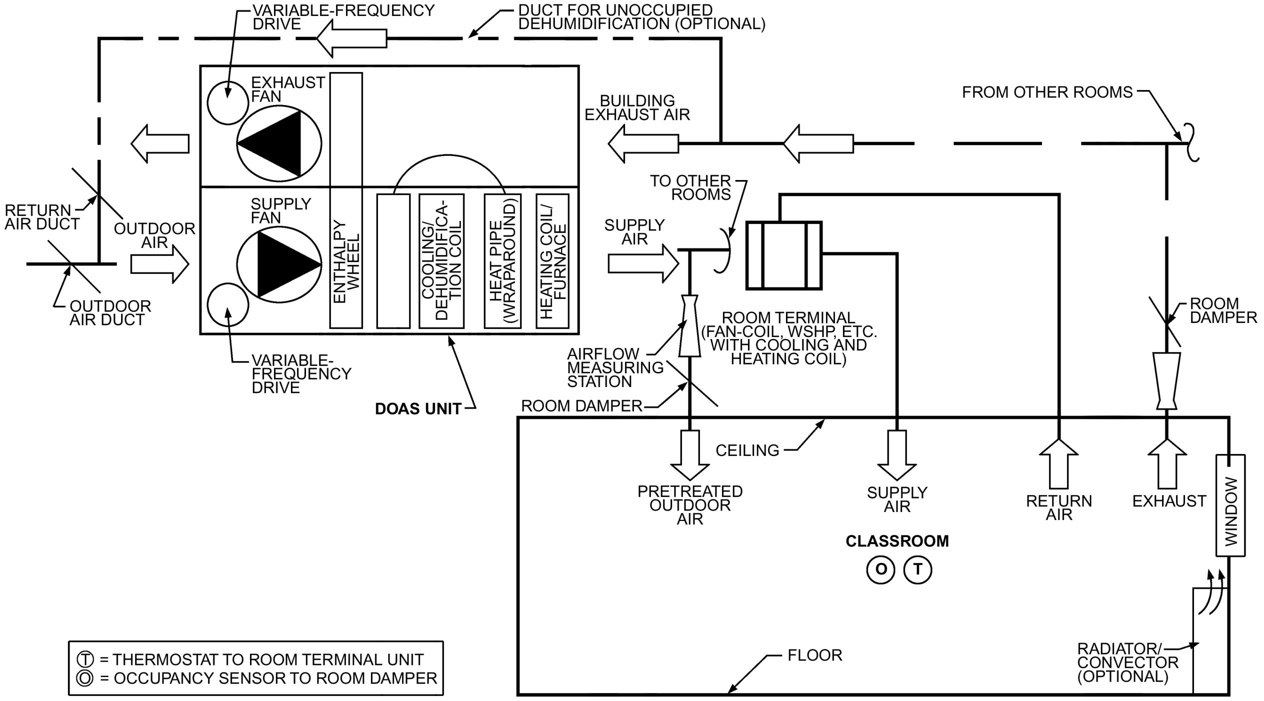


Fig. 4 Typical Schematic of DOAS with Local Classroom Cooling/Heating Terminal

exhausted at or close to the ceiling. After being discharged at a low level, the colder supply air rises as it is heated by heat sources (e.g., people, computers), also allowing effective removal of containments generated in the room.

Guidelines and procedures for designing displacement ventilation systems can be found in California Energy Commission (2006), Chen and Glicksman (2003), Skistad et al. (2002), Chapter 20 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment,* and Chapter 57 of this volume, which provides a classroom-based example.

Typical displacement ventilation systems for classrooms include the following main subsystems (Figure 6):

- DOAS air-handling unit that can cool and dehumidify outdoor air to 15 to 17°C and 5 to 7 g/kg for summer, and heat air to 18 to 20°C for winter
- Zone fan-powered terminal with sensible cooling capability (located outside the conditioned zone)
- Special displacement ventilation diffusers
- Heating radiators or convectors placed below windows in perimeter zones
- Control systems (thermostats and occupancy sensors)

In addition to the traditional displacement ventilation system described previously, displacement ventilation with induction can also be considered for classrooms. A displacement ventilation system with induction uses special terminals to provide additional cooling and heating with the displacement ventilation effect. These terminals are not equipped with fans, resulting in lower noise levels as required by more stringent noise criteria.

A displacement ventilation system with induction includes the following main subsystems:

- DOAS air-handling unit that can cool and dehumidify outdoor air to 12 to 14°C and 5 to 7 g/kg for summer, and heat air to 18 to 20°C for winter

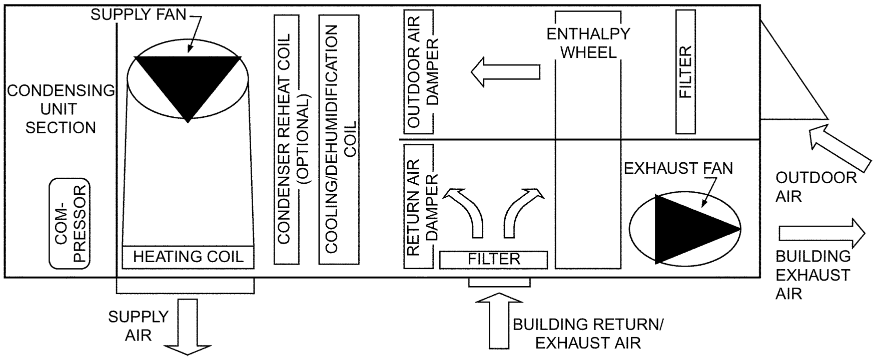


Fig. 5 Typical Configuration of Rooftop Packaged Air Conditioners with Energy Recovery Module and Enhanced Dehumidification (Condenser Reheat Coil)

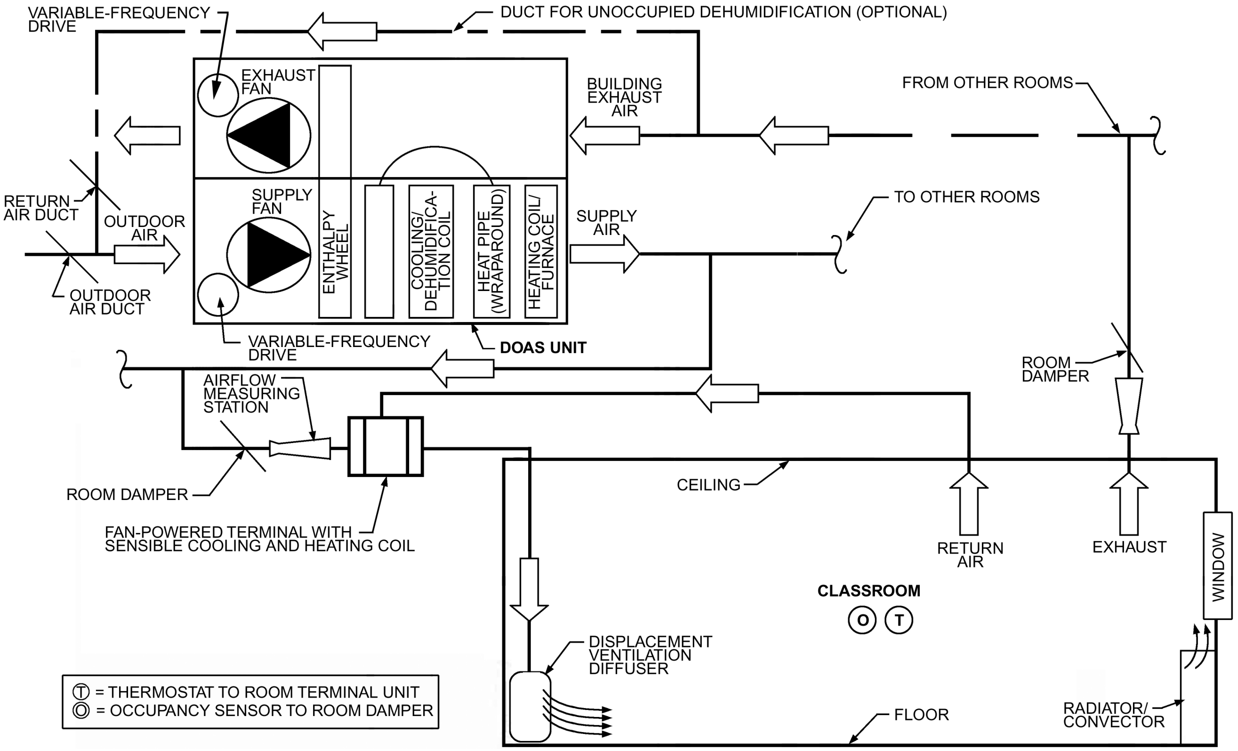


Fig. 6 Typical Displacement Ventilation System Layout

Table 11 Applicability of Systems to Typical Areas

	Cooling/Heating Systems								
	Centralized			Decentralized				Heating Only	
Typical Area[c]	SZ[a]	VAV/ Reheat	Fan Coil (Two- and Four-Pipe)	PSZ/ SZ[a] Split/ VRF	PVAV/ Reheat	WSHP	Geothermal Heat Pump and Hybrid Geothermal Heat Pump	Baseboard/ Radiators	Unit Heaters
Classrooms	X	X	X	X	X	X	X	X	
Laboratories and Science Facilities[b]	X	X	X	X	X	X	X	X	
Administrative Areas	X	X	X	X	X	X	X	X	
Gymnasium[e]	X	X		X					X
Libraries	X	X	X	X	X	X	X	X	
Auditorium[e]	X	X		X	X				
Home Economics Room	X	X	X	X	X	X	X	X	
Cafeteria[e]	X			X					
Kitchen[e]	X			X					X
Auto Repair Shop									X
Industrial Shop									X
Locker Rooms								X	X
Ventilation (Outdoor Air)	DOAS	[d]	DOAS	DOAS[f]	[d]	DOAS	DOAS	DOAS	DOAS

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

Notes:

[a] SZ and PSZ/SZ split for classrooms requires individual thermostatic control.

[b] Systems for laboratories must comply with local codes and be in accordance with current practices for laboratories.

[c] Systems and equipment for ice rinks and natatoriums not shown; refer to specialized equipment section.

[d] Special attention should be given for adequate OA supply in VAV applications without DOAS; consult ANSI/ASHRAE *Standard* 62.1-2013 Section 6.2.5.

[e] In some cases, these areas can be served by SZ, WSHP, and geothermal HP systems without OA from DOAS.

[f] When percentage of outdoor air dictates use of energy recovery in SZ or PSZ unit, OA for DOAS may not be required.

- Zone displacement ventilation with induction terminal, equipped with two- or four-pipe cooling and heating coil mounted along perimeter walls and windows
- Control systems (thermostats and occupancy sensors)

Active (Induction) Chilled Beams. Recently, the use of active/induction chilled beams for classrooms and other areas in educational facilities has been extended for enhanced IAQ, thermal comfort, and energy conservation. As with displacement ventilation with induction, an active/induction chilled beam terminal includes special small air jets that induce room air to flow through cooling or heating coils, depending on the system (two- or four-pipe). The primary air is outdoor air pretreated in a DOAS unit, as described previously. Figure 7 shows the principle of active/induction chilled beam terminals.

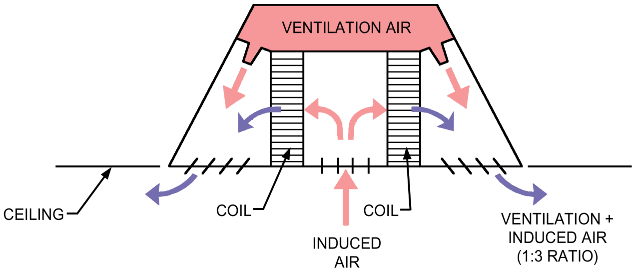


Fig. 7 Typical Active/Induction Chilled-Beam Terminal
(Rumsey and Weale 2006)

Although more room space is required for chilled-beam induction, these systems allow significant size and capacity reductions in air-handling systems, and decouple sensible cooling and heating from ventilation and humidity control. Temperatures of chilled water distributed to the chilled-beam terminals are typically elevated to around 13°C, which can reduce energy consumption. Hot water can be provided from a standard hot-water boiler at 66 to 82°C, or lower if condensing boilers applied.

An active/induction chilled-beam system typically includes the following main subsystems:

- DOAS unit that can cool and dehumidify outdoor air to 12 to 14°C and 5 to 7 g/kg for summer, and heat air to 18 to 20°C for winter
- Zone active/induction chilled-beam terminal, equipped with two- or four-pipe cooling and heating
- Control systems (thermostats and occupancy sensors)

Specialized Equipment. Areas such as natatoriums and ice rinks need specialized equipment to address the unique design requirements and the cooling, dehumidification, and heating characteristics of these areas. Natatoriums typically use special units that can introduce large quantities of outdoor air and allow active humidity control (mainly dehumidification). This equipment is similar to DOAS, and typically uses chilled water or a DX system for dehumidification. For systems with air-cooled condensers, condenser heat can be recovered to heat the swimming pool. See Chapter 5 of this volume for more information on natatoriums. Similarly, an ice rink requires special equipment; selection depends heavily on the school's location and seasonal use. Ice rink HVAC and dehumidification equipment can be desiccant-based or self-contained mechanical refrigeration. See Chapter 5 of this volume and Chapter 44 of the 2014 *ASHRAE Handbook—Refrigeration* for more information on ice rinks.

Chapters 27 and 28 of Harriman et al. (2001) also provide detailed information on humidity control for natatoriums and ice rinks, respectively.

Demand Control Ventilation (DCV). Demand control ventilation can reduce the cost of operating the HVAC systems. To ensure proper IAQ and comply with ANSI/ASHRAE *Standard* 62.1-2013 and local codes that allow DCV, the designer must carefully follow section 6.2.7 (Dynamic Reset) of ANSI/ASHRAE *Standard* 62.1.

ANSI/ASHRAE *Standard* 62.1-2013 explicitly allows use of CO_2 levels or occupancy to reset intake airflow in response to space occupancy levels. Pay special attention to the area served by the HVAC system and the system type. Areas such as gymnasiums and auditoriums can benefit from CO_2-based DCV, commonly used in single-zone systems without DOAS, serving one space with varying occupancy. In these cases, DCV control is simple, reliable, and cost-effective. Systems such as multizone VAV with recirculated air without DOAS require special attention to ensure adequate OA supply to multiple zones under varying loads (such as classrooms). This problem complicates the design, operation, and maintenance of DCV control systems and also adds the cost of additional sensors.

A simpler approach for DCV is in systems that use DOAS: the OA supply to each individual space can be controlled independently by occupancy sensors that can reduce the OA to a preset value (and also turn off the lights), or by CO_2 sensors (see Figure 4).

3. COLLEGES AND UNIVERSITIES

General and Design Considerations

College and university facilities can be a campus, cluster of buildings, or a single isolated building. Some colleges and universities have satellite campuses scattered throughout a city or a state. The design criterion for each building is established by the requirements of its users. The following are major facilities commonly found on college and university campuses.

Libraries/Learning Centers. Libraries and learning centers are central to the purpose of modern college and university. A library can be a collection of printed and electronic material and/or a place where individuals or groups of students gather for study or other academic activities. A typical library includes the following areas:

- Collection/stacks
- Library staff and services
- Main reading room
- Specialty areas (special collections, music and audiovisual resources, computer areas, etc.)
- Support areas

Temperature and humidity control is needed for maintaining the printed materials and the collections. Proper air distribution can be challenging because of different ceiling heights, stacks, mezzanines, etc. Reading rooms require air supply without draft, and special collections or rare books areas need a dedicated air-handling system. Noise also is critical in libraries; an acoustic consultant must review or be part of the mechanical design. See Chapter 23 for specifics on HVAC design for libraries.

Academic Buildings and Professional Schools. These buildings accommodate classrooms, which are the core of the university teaching and learning experience. There are two main categories of classrooms, with several subcategories (Neumann 2003):

Flat-floor classrooms are typically rectangular, basic, and easily reconfigurable for different teaching needs. In most cases, the number of students is relatively low. Sometimes, a larger flat-floor room can be subdivided to smaller rooms by folding or sliding partitions.

Sloped-floor classrooms are used when the class size exceeds the point where all the students can see each other clearly in a flat-floor classroom. Sloped-floor classrooms typically have more than 40 students. Those with a capacity of 250 students or more are generally referred as auditoriums, which require theater design consideration.

Academic buildings also have faculty offices and auxiliary areas to support teaching activities. Professional schools are typically allocated to a specific academic discipline. Each of these schools has specific needs, depending on the academic requirements. The HVAC design and systems for classrooms and other administrative areas are similar to classrooms in high schools (see Table 11).

Science Teaching and Research Facilities. College and universities science facilities accommodate highly specialized areas for teaching and research in several disciplines (e.g., chemistry, biology, physics). Teaching facilities are designed mainly for group instruction, typically with one or more instructors and 12 to 32 students; an average-sized teaching lab can accommodate 24 students. The laboratory should be designed to support a range of activities for various courses: for example, a chemistry lab should be able to handle introductory chemistry, organic chemistry, etc.

Research facilities can be part of a science teaching building or grouped in a stand-alone research facility. Research facilities are customized and designed for graduate and postgraduate students, typically under the direction and supervision of several principal investigators (PIs). Unlike teaching labs, which are designed for large group instruction, research labs should be designed to accommodate the activities of individuals or small groups. Given potentially hazardous activities in teaching and research labs, the most critical factor in designing systems for labs is safety; this concern has major implications on the design of HVAC and mechanical systems.

Teaching and research labs may contain fume hoods, machinery, lasers, vivariums, areas with controlled environments, and departmental offices. The HVAC systems and controls must be able to accommodate diverse functions of the facility, which may have 24 h, year-round operation, and yet be easy to service and quick to repair. Variable-air-volume (VAV) systems can be used. Proper control systems should be applied to introduce and extract the required quantities of supply and exhaust air. Maintaining the required space pressure differential to adjacent spaces and the minimum airflow under all circumstances is extremely critical for safe laboratory operation. Energy can be saved by recovering energy from exhaust air and tempering outdoor makeup air. Pay special attention to containment in the exhaust air stream. Examine potential carryover of air from exhaust to supply, and interaction with the energy recovery device adsorbent for cases with total (sensible and latent) energy recovery. In general, air exhausted from fume hoods should not be used for energy recovery. Where heat recovery from fume hoods exhaust is considered, careful coordination with the site health and safety (H&S) officer is required. Other energy-saving systems used for laboratory buildings include (1) active chilled beams (Rumsey and Weale 2006), (2) ice storage, (3) heat reclaim chillers to produce hot water for domestic use or for booster coils in the summer, and (4) cooling tower free cooling.

The design engineer should discuss expected contaminants and concentrations with the owner to determine construction materials for fume hoods and fume exhaust systems. Close coordination with H&S personnel is vital for safe laboratory building operation. Backup or standby systems for emergency use should be considered, such as alarms on critical systems. Maintenance staff should be thoroughly trained in upkeep and repair of all systems, components, and controls. For design criteria and other design information on laboratories and vivariums, see Chapter 16, ANSI/AIHA *Standard* Z9.5-2012, DiBerardinis et al. (2013), and McIntosh et al. (2001). Additional information on energy conservation in labs can be found on the Labs 21 web site (http://labs21benchmarking.lbl.gov/).

Some research facilities include vivariums (animal facilities). These spaces are commonly associated with laboratories, but usually have their own separate areas. Additional areas that can found in vivariums are necropsy rooms, surgery suites, and other specialty areas. Animal facilities need close temperature control and require a significant amount of outdoor ventilation to control odors and prevent the spread of diseases among the animals. Animal facilities are discussed in Chapters 16 and 24, and by the National Research Council (NRC 1996).

Housing

Student Housing. Housing is an integral part of student's academic and social life. Student housing traditionally had few amenities, and the emphasis for years was economy and reduced construction cost. Today, more housing administrators are changing this philosophy by providing an enhanced, rich on-campus residential life. Student and staff housing facilities include the following:

- Dormitories (residence halls)
- Suites
- Apartments and studios
- Couples housing

Dormitories (residence halls) are typically for freshman students. Student living units are generally single- or double-occupancy rooms that open directly to a corridor. The building can be a high rise or low rise, depending on the setting or the location of the campus. Typically, there are two students per room, with one single-occupancy room reserved for the resident assistant. On the ground floor are public facilities, which may include a living room, reception desk, kitchen/lounge, and cafeteria. Dorm rooms typically do not have individual kitchens or bathrooms; communal bathrooms usually serve one floor.

Suites are typically occupied by older undergraduate students. The suite plan typically connects four to six double-occupancy sleeping room rooms with a shared bathroom and living room.

Apartments and **studios** are typically occupied by upper-division and graduate students, and are basically suites with kitchens and private bathrooms. Apartments and studios are the most desirable housing and are the most expensive because of their additional plumbing and electrical systems.

Couples housing generally consists of one-, two-, or three-bedroom apartments in separated complexes. A couples housing facility may have a section for married couples, who often have young children whose safety and security needs must be considered. These facilities may have outdoor play areas and child care facilities.

Faculty Housing. Faculty members typically find housing outside the campus, but the high cost of local living has convinced many universities that offering on-campus housing will attract the best candidates to their academic institution. This type of housing is similar to typical residential housing and can include duplexes, apartments, townhouses, and single-family homes.

Air conditioning in campus housing for students and faculty should be quiet, easily adjustable, and draft free. Systems that require little space and have low total owning and operating costs should be selected. Table 12 lists design criteria for housing facilities.

Typically, decentralized systems with DOAS or air-to-air energy recovery should be used for these applications:

- Water-source heat pumps (WSHPs), also known as water-loop heat pumps (WLHPs)
- Geothermal heat pumps (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), where there is limited area for the ground-coupled heat exchanger or where it is economically justified
- Light commercial split systems
- Minisplit and variable-refrigerant-flow (VRF) units
- Fan-coil units

When dormitories are closed during winter breaks, the heating system must supply sufficient heat to prevent freeze-up. If the dormitory contains nondwelling areas, such as administrative offices or eating facilities, these facilities should be designed as a separate zone or with a separate system for flexibility, economy, and odor control. Solar energy can be considered for domestic hot water (DHW).

Athletics and Recreational Facilities

College and university sports facilities ranging from large arenas for ice hockey, basketball, and other spectator sports, to small gymnasiums and fitness centers. College sports activities are heavily influenced by intercollegiate sports, which are governed by extensive standards and regulations of the National Collegiate Athletic Association (NCAA). A university's participation in intercollegiate sports is well known to be an important revenue source and is often critical in prospective students' decision-making processes. Typical sports facilities that can be found in universities campuses are

- Collegiate arenas (indoor sport arenas dedicated to a particular sport, or multipurpose)
- Gymnasiums (for activities such as physical education)
- Field houses (for outdoor activities to be played indoors during bad weather)
- Natatoriums
- Recreation centers (multipurpose activity courts, fitness/weight room)

Chapter 5 of this volume covers design practices for several of these facilities. For ice rinks and arenas, consult Chapter 44 of the 2014 *ASHRAE Handbook—Refrigeration* and Chapter 27 of Harriman et al. (2001) (which covers natatoriums, as well).

Social and Support Facilities

Social and support facilities and campus centers include common areas designed to improve and expand student services: for example, auditoriums, lounges, lobbies, dining and food services, offices and administration, libraries, cafés and snack bars, classrooms, meeting rooms, bookstores and other retail areas, banks, printing shops, etc. Given this variety of applications, the reader should refer to Chapters 2, 3, 5, 23, and 33 of this volume, and other application-specific sources for the design of HVAC&R systems for these areas.

Table 12 Housing Rooms Design Criteria[a]

	Inside Design Conditions							
	Winter		Summer					
Category	Temperature	Relative Humidity[b]	Temperature	Relative Humidity	Combined Outdoor Air Rate[c]	Exhaust[d]	Filter Efficiency[e]	Noise, RC (N);QAI < 5 dB Level[f]
Dorm, suite rooms	21 to 23°C	30 to 35%	23 to 26°C	50 to 60%	11 L/s	NR	6 to 8 MERV	30
Apartments and studio rooms	21 to 23°C	30 to 35%	23 to 26°C	50 to 60%	42.5 L/s	37.5 L/s	6 to 8 MERV	30
Couple and faculty housing	21 to 23°C	30 to 35%	23 to 26°C	50 to 60%	42.5 L/s	37.5 L/s	6 to 8 MERV	30

NR = not required.

[a] This table should not be used as the only source for design criteria. The data contained here can be determined from ASHRAE handbooks, standards, and governing local codes.

[b] Minimum recommended humidity.

[c] Per ASHRAE *Standard* 62.1-2013, based on two occupants for room. For areas with exhaust, ventilation is based on exhaust requirements.

[d] Air exhaust from bathroom, toilet, and kitchen areas.

[e] Per ASHRAE *Standard* 52.2-2012.

[f] Based on Chapter 48.

Cultural Centers

Universities and colleges with cultural facilities and academic programs such as music, theater, dance, and visual arts enhance the cultural and artistic lives of students. The two main cultural facilities are performing arts and visual arts centers. Several areas are common for both these areas are

- **Public support areas,** which include lobby, student common, café, gift shop, box office, coat room, and restroom facilities
- **Administration/faculty areas,** including offices, administration areas, and conference rooms
- **Back of the house,** such as loading docks, shipping and receiving, maintenance and building operation, mechanical rooms, and control rooms

Unique areas for **performing arts** are

- **Performance spaces,** including seating areas, stage, orchestra pit, dimmer room, audio rack room, and lighting and sound control
- **Backstage/performer support,** such as the green room, dressing rooms, wardrobe, laundry, and storage
- **Theater, music, and dance instruction areas,** which include rehearsal rooms, dance studios, instrumental rehearsal rooms, listening labs, and music and instrument storage

Unique areas for **visual arts** are

- **Museums,** which include art galleries, workrooms, art storage, and conservation areas
- **Fine arts instruction rooms,** comprising design, drawing, painting, print making studios, photographic darkrooms, and library
- **General arts instruction,** such as lecture halls, classrooms, seminar rooms, and computer labs

Cultural centers encompass a large number of specialty areas, and careful attention required when designing, constructing, and maintaining the HVAC&R systems. Consult Chapters 2, 3, 5, and 23 for details.

Central Utility Plants

Universities and college campuses typically have large central utility plants or smaller mechanical rooms serving an individual building or cluster of buildings. The central utility plants can supply chilled water, steam, and electrical power or only steam or chilled water. In these cases, chilled water, steam, or hot water is generated at a building level or in one smaller utility plant serving a cluster of buildings. The setup depends heavily on site constraints, including geographic location. The central utility plant comprises chillers, boilers, steam specialties, primary and secondary pumps, cooling towers, heat exchangers, combined heat and power (CHP) prime movers, and CHP auxiliary equipment, electrical power transformers, switchgears, control systems, etc. In the 2012 *ASHRAE Handbook—HVAC Systems and Equipment*, see Chapter 3 for design of central heating and cooling plants, Chapter 7 for CHP, Chapter 11 for steam systems, and Chapter 12 for district heating and cooling.

In addition to accommodating the mechanical and electrical equipment, central utility plants also house engineering, operation, and maintenance personnel. Central plants are not conditioned but generally are heated and ventilated; storage areas, shops, and other support areas are heated, ventilated, or cooled, depending on the use. Offices, administration areas, and control rooms are typically fully conditioned.

Where economically justifiable, chilled water and steam can be purchased from an independent operator

4. SUSTAINABILITY AND ENERGY EFFICIENCY

A trend in the educational community to embrace the principles of sustainable design has increased in the last several years. Begun as a means to educate the students in conserving earth resources, this approach also provides benefits such as enhanced IAQ and lower operating costs.

There are several definitions of sustainability, green buildings, and high-performance buildings. In the context of this chapter, these terms refer 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. Because energy efficiency is the area of expertise of the HVAC&R designer, this section covers these topics in more detail.

Several tools and mechanisms are available to assist the HVAC&R designer in designing and demonstrating sustainable educational facilities; the following are the most common tools:

Advanced Energy Design Guide (AEDG) for K-12 Schools

The *Advanced Energy Design Guide for K-12 Schools* (ASHRAE 2008) was developed to help designers of K-12 facilities achieve energy savings of at least 30% compared to ANSI/ASHRAE/IESNA *Standard* 90.1-1999. The guide can be downloaded from the ASHRAE web site at http://www.ashrae.org/publications/page/1604.

An updated version of the *Advanced Energy Design Guide for K-12 Schools* (ASHRAE 2011) is also available to help designers of K-12 facilities achieve energy savings of at least 50% compared to ANSI/ASHRAE/IESNA *Standard* 90.1-2004. This guide can be downloaded from the ASHRAE web site at https://www.ashrae .org /standards-research--technology/advanced-energy-design-guides /50-percent-aedg-free-download.

These guides provides recommendations for energy-efficient design based on geographic location, covering issues such as envelope, lighting, HVAC, and service water heating (SWH).

ASHRAE/USGBC/IES *Standard* 189.1-2011

This standard provides minimum requirements for the siting, design, construction, and plan for operation of high performance, green buildings to

- Balance environmental responsibility, resource efficiency, occupant comfort and well-being, and community sensitivity
- Support the goal of development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

This standard provides minimum criteria that apply to the following elements of building projects:

- New buildings and their systems
- New portions of buildings and their systems
- New systems and equipment in existing buildings

The standard addresses site sustainability, water use efficiency, energy efficiency, indoor environmental quality (IEQ), and the building's impact on the atmosphere, materials, and resources.

Leadership in Energy and Environmental Design (LEED®)

Many schools are seeking LEED certification from the U.S. Green Building Council (USGBC). The LEED for Schools (USGBC 2009a) rating system is unique to the design and construction of K-12 schools.

The system awards credits in seven categories:

1. Sustainable sites (SS)
2. Water efficiency (WE)
3. Energy and atmosphere (EA)
4. Materials and resources (MR)
5. Indoor environmental quality (IEQ)
6. Innovation and design process (ID)
7. Regional priority (RP)

Categories 1 to 5 include prerequisites, which are mandatory for certification, and credits. The last two categories are credits only.

Typically, the HVAC&R designer is heavily involved in the (1) energy and atmosphere and (2) indoor environmental quality categories. In the EA category, the HVAC&R designer, along with the architect, electrical engineers, and plumbing engineers, demonstrate compliance with prerequisite EA 2 by using the following procedures:

- Option 1: Whole-building energy simulation, by demonstrating 10% improvement (for new construction) or a 5% improvement in the proposed building performance rating for major renovations to existing buildings over ANSI/ASHRAE/IESNA *Standard* 90.1-2007.
- Option 2: Prescriptive compliance path, for less than 18 587 m Must comply with all the prescriptive measures identified in ASHRAE (2011). Projects outside the United States may use ASHRAE/ASHRAE/IESNA *Standard* 90.1-2007, Appendices B and D, to determine the appropriate climate zone.
- Option 3: Prescriptive compliance path (New Buildings Institute 2007), for less than 9294 m^2.

Additional EA credits can be obtained by demonstrating additional energy cost savings compared to the ANSI/ASHRAE/IESNA *Standard* 90.1-2007's Appendix G and from other sections of the EA group, such as on-site renewable energy, enhanced commissioning, measurement and verification, and green power. In addition, the HVAC&R designer is involved in issues of indoor environmental quality; these issues are typically associated with minimum and enhanced ventilation, acoustics, thermal comfort, controls, daylighting, mold prevention, etc.

Details and additional information on new construction and major renovations of K-12 facilities or previous editions of LEED for Schools can be found on the USGBC web site at http://www.usgbc.org/leed.

For existing schools, the LEED rating system for existing buildings can be applied (see USGBC web site).

ENERGY STAR for K-12 Facilities

Similarly to appliances, a building or manufacturing plant can earn the ENERGY STAR label. An ENERGY STAR-qualified facility meets strict energy performance standards set by the U.S. EPA and uses less energy, is less expensive to operate, and causes fewer greenhouse gas emissions than its peers. To qualify, a building must score in the top 25% based on the EPA's National Energy Performance Rating System, which considers energy use among other, similar types of facilities (including K-12 educational facilities) on a scale of 1 to 100. This rating system accounts for differences in operating conditions, regional weather data, and other important considerations.

To determine eligibility for the ENERGY STAR label, as well as LEED-EB certification, the EPA's free online tool Portfolio Manager can be used (http://www.energystar.gov/benchmark). If the school facility scores 75 or higher (of a maximum of 100) using Portfolio Manager, a professional engineer (PE) will verify and approve the analysis. Detailed procedures for earning the ENERGY STAR labels can be found at http://www.energystar.gov, including case studies, useful information for educational facilities, and a list of professional engineers who provide free verification services.

Collaborative for High Performance Schools (CHPS)

CHPS (http://www.chps.net) is leading a national movement to improve student performance and the entire educational experience by building the best possible schools. CHPS provides useful information for designing and maintaining high-performance schools. The following is a list of best practices and information available from CHPS:

- Planning for high-performance schools
- Design for high-performance schools
- Maintenance and operations of high-performance schools
- Commissioning of high-performance schools
- High-performance relocatable classrooms

In addition, lists of CHPS criteria for several states are available.

Laboratories for the 21st Century (Labs21)

Laboratories for the 21st Century [Labs21; EPA (2010)] is designed to meet the needs of facility designers, engineers, owners, and facility managers of laboratory and similar high-performance facilities. Cosponsored by the EPA and DOE, Labs21 offers the opportunity for worldwide information exchange and education.

The primary guiding principle of the Labs21 approach is that improving a facility's energy efficiency and environmental performance requires examining the entire facility from a whole-building perspective. This perspective allows owners to improve the efficiency of the entire facility, rather than focusing on specific building components. The Labs21 program provides excellent information for laboratory design, energy conservation, best practices, and tools, such as the following:

- Introduction to low-energy design
- Design guide for energy-efficient research labs
- Best practice guides
- Case studies
- Energy benchmarking
- Laboratory equipment efficiency wiki
- Environmental performance criteria
- Design intent tool
- Labs21 design process manual

Additional information can be found at http://www.labs21century.gov/.

EnergySmart Schools

The EnergySmart Schools (U.S. DOE 2009) program provides energy efficiency information on planning, financing, design build and operation and maintenance of schools at http://energy.gov/sites/prod/files/2013/11/f5/ess_o-and-m-guide.pdf.

Other Domestic and International Rating Systems

Additional domestic and international systems are shown in Table 13.

5. ENERGY CONSIDERATIONS

Energy standards such as ANSI/ASHRAE/IESNA *Standard* 90.1-2013 and local energy codes should be followed for minimum energy conservation criteria. Because the HVAC&R designer deals mostly with the mechanical systems, Table 14 presents a list of selected energy conservation measures. Note that additional measures such as modifications to lighting, motors/drives, building envelope, and electrical services should be considered for energy reduction. Energy procurement or supply-side opportunities should also be investigated for energy cost reduction.

6. ENERGY MEASUREMENT AND VERIFICATION (M&V)

Energy measurement and verification (M&V) is the process of measuring and verifying both energy and cost savings resulting from implementation of an energy conservation measure. An energy conservation measure is defined as the installation or modification of energy using equipment, or systems, for the purpose of reducing energy use and/or costs.

M&V should be used by anyone wishing to prove the achievement of savings in utility resources, such as energy and water, delivered through any type of savings project or program. This typically includes

- Building owners and managers
- Facility managers, plant and process engineers,
- Energy service companies (ESCO) and other energy services professionals, such as energy auditors and energy management consultants, who provide advice or deliver energy savings through an energy performance (EPC), or other contracting arrangements

Table 13 Summary of Domestic and International Rating Systems

Rating System	Country
BRE Environmental Assessment Method (BREEAM)	U.K.
Comprehensive Assessment System for Building Environmental Efficiency (CASBEE)	Japan
Germany Sustainable Building Certificate (DGNB)	Germany
Green Building Evaluation Standard (Three-Star System)	China
Green Globes System	Canada
Green Star	Australia
Hong Kong Building Environmental Assessment Method (HK-BEAM)	China (Hong Kong only)
National Green Building Standard	United States

Table 14 Selected Potential Energy Conservation Measures

Category	Description
HVAC Air Side	DDC systems upgrade Variable-speed drives on fan motors Conversion from constant volume (CV) to variable air volume (VAV) Air-side economizer Temperature set point adjustments Exhaust fume hood controls modifications Reheat minimization DOAS and air-to-air energy recovery Destratification fans Airflow reduction and air-side retrocommissioning in laboratories Active chilled beams (classrooms, laboratories, etc.) Natural ventilation (where applicable) Evaporative cooling (where applicable)
Chiller Plants	Chiller plant operation optimization (hydronic system) Chiller(s) replacement Chiller energy source switching Heat recovery (from CHP) driven chiller Cooling tower repair, optimization, replacement Cooling tower water treatment optimization Cooling tower fans conversion to variable speed Water-side free cooling Conversion of DX system to chilled water Offline chiller isolation Chilled/condenser water temperature reset Thermal storage
Boiler Plants	Boiler optimization/replacement Burner optimization/replacements Oxygen and excess air trim controls Conversion of linkage-based burner control to parallel positioning (servo motors) Dual-fuel switching/capability Boiler heat recovery (stack economizer) Condensing boilers Boiler temperature reset Offline boiler isolation Automatic blowdown control Blowdown heat recovery Condensate systems upgrade and optimization Feed water delivery improvements Water treatment optimization
Steam and Chilled-Water Distribution	Steam distribution pressure control Steam trap repair/replacement/program Insulation repairs/upgrade Piping balancing Variable-speed pumping Primary/secondary piping Conversion from constant flow to variable flow
Energy Management and Control Systems	LAN systems/network interfacing Equipment sequencing Conversion to DDC system Space temperature setback and setup Demand control ventilation (DCV) Chiller plant efficiency monitoring (see ASHRAE *Guideline* 22-2008) Boiler plant efficiency monitoring (steam flow and gas flow) Duty cycling Chiller plant control optimization Boilers sequencing optimization Load shedding Remote communications Equipment performance and energy use monitoring Preventive/predictive maintenance Automated/web-based fault detection and diagnostics (FDD) Airflow and water flow measurements Energy metering and submetering Emissions and/or CO_2 tracking
Central Plant Supply Side and Renewable Energy	Combined heat and power (CHP) Solar energy (thermal) Photovoltaic applications Wind energy Geothermal energy and hybrid geothermal systems
Domestic Hot Water	Condensing water heaters Demand (tankless or instantaneous) water heaters Heat pump water heaters Solar domestic water heater and pool water heating

Source: Adapted from Petchers (2002).

Energy M&V essentially compares energy use before and after an energy retrofit, taking in account and adjusting for nonretrofit changes (e.g., weather, occupancy schedules) that affect energy use. These variables must be removed to objectively calculate the energy savings from the energy conservation measure. Chapter 41 provides additional information on M&V.

The following is a short overview of M&V methodologies from the two major authorities.

ASHRAE *Guideline* 14-2002

ASHRAE *Guideline* 14-2002 is a reference for calculating energy and demand savings associated with performance contracts. In addition, it sets forth instrumentation and data management guidelines and describes methods for accounting for uncertainty associated with models and measurements; for compliance, the overall uncertainty of savings estimates must be below prescribed thresholds. It does not discuss other issues related to performance contracting. *Guideline* 14 describes three M&V procedures. The three approaches are closely related to and support the options provided in IPMVP:

- **Whole-building approach.** This approach uses a main meter to measure energy flow to the whole building, a group of buildings, or separate sections of a building. Energy flow is usually electric, gas, oil, and thermal. One or more of the systems served by the meter may have energy conservation measures (ECMs) applied. This approach may involve using monthly utility bill data, or data gathered more frequently from a main meter.
- **Retrofit isolation approach.** This approach uses meters to isolate energy use and/or demand of ECM-controlled subsystems (e.g., lighting, chiller, boiler) from that of the rest of the facility. These measurements may be made once before and once after the retrofit, periodically, or continuously. Savings derived from isolated and metered systems may be used as a basis for determining savings in similar but unmetered systems in the same facility, if they are subjected to similar operating conditions throughout the baseline and post-retrofit periods.
- **Whole-building calibrated simulation approach.** This approach involves using a computer simulation tool to create a model of the facility's energy use and demand. The model, which is typically of pre-retrofit conditions, is calibrated or checked against actual measured energy use and demand data, and possibly other operating data. The calibrated model is then used to predict energy use and demand under post-retrofit conditions. Savings are derived by comparing modeled results under the two sets of conditions, or by comparing modeled and actual metered results.

International Performance Measurement and Verification Protocol (IPMVP 2007)

The IPMVP groups M&V methodologies into four general categories (Table 15). The options are generic M&V approaches for energy and water saving projects. As in ASHRAE *Guideline* 14, the IPMVP M&V approaches are divided into two general types: retrofit isolation and whole facility. Retrofit isolation methods look only at the affected equipment or system independent of the rest of the facility; whole-facility methods consider the total energy use and deemphasize specific equipment performance.

Energy Efficiency and Integrated Design Process (IDP)

An integrated design process (IDP) is vital for the design of high-performance educational facilities. Chapter 58 covers the concept of

Table 15 IPMVP M&V Options

M&V Option	Performance[a] and Usage[b] Factors	Savings Calculation
Option A: Retrofit Isolation with Key Parameter Measurement	Based on combination of measured and estimated factors when variations in factors are not expected. Measurements are spot or short-term and taken at component or system level, in both baseline and postinstallation cases. Measurements should include key performance parameter(s) that define ECM's energy use. Estimated factors are supported by historical or manufacturer's data. Savings determined by engineering calculations of baseline and postinstallation energy use based on measured and estimated values.	Direct measurements and estimated values, engineering calculations and/or component or system models often developed through regression analysis. Adjustments to models are not typically required.
Option B: Retrofit Isolation with All-Parameter Measurement	Based on periodic or continuous measurements of energy use taken at the component or system level when variations in factors are expected. Energy or proxies of energy use are measured continuously. Periodic spot or short-term measurements may suffice when variations in factors are not expected. Savings determined from analysis of baseline and reporting period energy use or proxies of energy use.	Direct measurements, engineering calculations, and/or component or system models often developed through regression analysis. Adjustments to models may be required.
Option C: Utility Data Analysis (Whole Facility)	Based on long-term, continuous, whole-building utility meter, facility level, or submeter energy (or water) data. Savings determined from analysis of baseline and reporting-period energy data. Typically, regression analysis is conducted to correlate with and adjust energy use to independent variables such as weather, but simple comparisons may also be used.	Based on regression analysis of utility meter data to account for factors that drive energy use. Adjustments to models are typically required.
Option D: Calibrated Computer Simulation (Retrofit Isolation or Whole Facility)	Computer simulation software is used to model energy performance of a whole facility (or subfacility). Models must be calibrated with actual hourly or monthly billing data from the facility. Implementation of simulation modeling requires engineering expertise. Inputs to the model include facility characteristics; performance specifications of new and existing equipment or systems; engineering estimates, spot-, short-term, or long-term measurements of system components; and long-term whole-building utility meter data. After the model has been calibrated, savings are determined by comparing a simulation of the baseline with either a simulation of the performance period or actual utility data.	Based on computer simulation model (such as eQUEST) calibrated with whole-building, end-use metered data, or both. Adjustments to models are required.

Source: FEMP (2008).
Notes:
[a] Performance factors indicate equipment or system performance characteristics, such as kW/kW for a chiller or watts/fixture for lighting.
[b] Operating factors indicate equipment or system operating characteristics such as annual cooling ton-hours for chillers or operating hours for lighting.

integrated building design (IBD) and IDP in detail, and additional information can be found on the Northwest Energy Efficiency Alliance's BetterBricks web site (http://www.betterbricks.com/schools) and http://designsynthesis.betterbricks.com/building-design.

Unlike the sequential design process (SDP), in which the elements of the built solution are defined and developed in a systematic and sequential manner, the integrated design process (IDP) encourages holistic collaboration of the project team during all phases of the project, resulting in cost-effective and environmentally friendly design. IDP is accomplished by responding to the project objectives, which typically are established by the owner before team selection. A typical IDP approach 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 58.

In high-performance buildings, the objectives are typically related to site sustainability, water efficiency, energy and atmosphere, materials and resources, and indoor environmental quality. These objectives are in fact the main components of several rating systems. As indicated previously, the HVAC&R designer is heavily involved in meeting energy efficiency objectives. Energy use objectives are typically the following:

- Meeting minimum prescriptive compliance (mainly local energy codes, ANSI/ASHRAE/IESNA *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., USGBC; LEED®; energy and atmosphere using ANSI/ASHRAE/IESNA *Standard* 90.1, Appendix G)
- Providing a facility/building site energy density [e.g., energy utilization index (EUI)] less than an owner-defined target (e.g., EPA, ENERGY STAR's Portfolio Manager)
- Providing a facility/building source energy density less than an owner-defined target
- Deriving 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 clarify 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 point. Examples include the following:

- Cooling/heating loads calculations tools
- Ductwork design
- Piping design
- Acoustics
- Equipment selection programs for air-handling units, packaged rooftop units, fans, chillers, pumps, diffusers, etc.

These tools are used to specify cooling and heating capacities, airflow, water flow, equipment size, etc., at a design point as defined and agreed by the client.

Energy modeling (or building modeling and simulation) is used to model the building's thermal behavior and the performance of building energy systems. Unlike design tools, which are used for one design point or for sizing, the building energy simulation analyzes the building and its systems up to 8760 times (or hour-by-hour, or in some cases 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, and so on. After these variables are defined, the simulation engine solves mathematical models of the building elements, equipment, etc., typically through a sequential process, 8760 times (one for every hour). Results include annual energy consumption, annual energy cost, hourly profiles of cooling loads, and hourly energy consumption. Chapter 19 of the 2013 *ASHRAE Handbook—Fundamentals* provides detailed information on energy modeling techniques.

Typically, energy modeling tools (or building energy simulation programs) have to meet minimum requirements to be accepted by rating authorities such as the USGBC and local building codes. The following is a typical minimum modeling capabilities for building energy simulation program:

- 8760 h per year
- Hourly variations in occupancy, lighting power, miscellaneous equipment power, thermostat set points, and HVAC system operation are 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
- Capable of performing design load calculations to determine required HVAC equipment capacities and air and water flow rates in accordance with generally accepted engineering standards and handbooks (e.g., *ASHRAE Handbook—Fundamentals*)
- Testing according to ASHRAE *Standard* 140

Energy modeling is typically used for the following applications:

- As a decision support tool to analyze several design alternatives and select the optimal solution for a given set of criteria for energy systems in new construction and retrofit projects.
- To provide vital information to the engineer about the building behavior and systems performance during the design stage
- To demonstrate compliance with energy standards such as ASHRAE *Standard* 90.1, section 11 (energy cost budget method)
- To support LEED certification in the energy and atmosphere (EA) section
- To model existing buildings and systems and analyze proposed energy conservation measures (ECMs) by performing calibrated simulation
- To 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 Schools (USGBC 2009a), energy and atmosphere (EA), prerequisite 2 (minimum energy performance), and for EA credit 1 (optimize energy performance). An energy simulation program meeting the preceding requirements and those of ASHRAE *Standard* 90.1, Appendix G, is used to perform whole-building energy simulation to demonstrate 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, comparing a building's normalized energy consumption to that of other similar buildings. The most common normalization factor is gross floor area. Energy benchmarking is less accurate than other energy analysis methods, but can provide a good overall picture of relative energy use.

Relative energy use is commonly expressed by an energy utilization index (EUI), which is the energy use per unit area per year. Typically EUI is defined in terms of MJ/m^2 per year. In some cases, the user is interested in energy cost benchmarking, which is known as the cost utilization index (CUI), with units of \$/m^2 per year. It is important to differentiate between *site* EUI and *source* EUI. Building energy use can be reported as the actual energy used on site (i.e., site EUI), or as energy used at the energy source (i.e., source EUI). 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 U.S. DOE Energy Information Administration's (DOE/EIA) Commercial Building Energy Consumption Survey (CBECS). Table 2 of Chapter 36 shows an example of EUI calculated based on DOE/EIA 2003 CBECS. As shown in that table, the mean site EUI for high schools is 765 MJ/yr per square meter.

The following is a list of common energy benchmarking tools:

- U.S. EPA ENERGY STAR Portfolio Manager (http://www.energystar.gov/benchmark)
- Lawrence Berkeley National Laboratory's (LBNL) Arch building comparison tool (http://poet.lbl.gov/arch/; for California, http://poet.lbl.gov/cal-arch/compare.html)
- Labs 21 for laboratory energy benchmarking (http://labs21benchmarking.lbl.gov)

An example of laboratory energy benchmarking (in I-P units) is shown in Figure 8.

Comprehensive information on energy benchmarking and available benchmarking tools can be found in Glazer (2006) and Chapter 36.

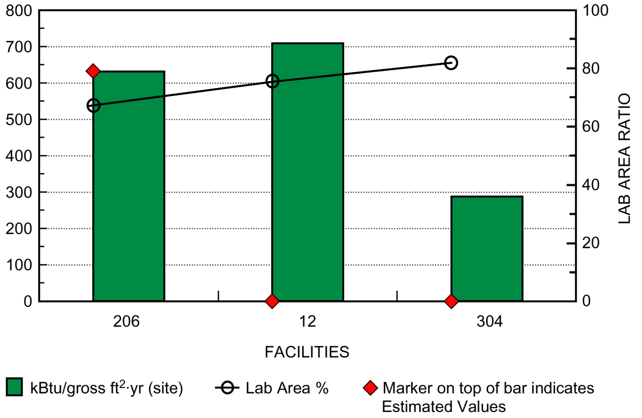
Combined Heat and Power in Educational Facilities

Combined heat and power (CHP) plants and building cooling, heating, and power (BCHP) can be considered for large facilities when economically justifiable. Chapter 7 of the 2012 *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 http://www.epa.gov/chp/
- U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, at http://www.energy.gov/eere/
- The U.S. DOE Midwest CHP Technical Assistance Partnership, at http://www.midwestchptap.org

A market analysis report by Ryan (2004) clearly suggests that secondary schools (9-12) are more suitable for BCHP than primary schools, because secondary schools

- Are more likely to operate 12 months a year
- Are more likely to contain an indoor swimming pool facility
- Are more likely to operate into the evenings and weekends, allowing longer period of BCHP operation
- Typically contain gymnasiums with shower facilities



METRIC	MINIMUM	AVERAGE	MAXIMUM	COUNT
TOTAL BUILDING kBtu/gross ft^2·yr (SITE)	285.78	542.37	708.61	3

FACILITY	LAB TYPE	YEAR	kBtu/gross ft^2·yr (site)	LAB AREA RATIO	OCCUPANCY HOURS PER WEEK	CLIMATE
206	Biological	2007	632.73	67%	108	5A
12	Biological	2001	708.61	75%	144	5A
304	Biological	2008	285.78	82%	100	5A

Fig. 8 Example of Laboratory Building Energy Benchmarking (Labs 21)

The EPA's Combined Heat and Power (CHP) Partnership (http://www.epa.gov/chp/project-development/index.html) web site can be consulted for procedures of conducting feasibility studies and evaluations for CHP integration.

Maor and Reddy (2008) describe a procedure to optimally size the prime mover and thermally operated chiller for a large school by combining a building energy simulation program and a CHP optimization tool.

A database of CHP installations is available at http://www.eea-inc.com/chpdata/.

CHP is more common for large colleges and universities than for primary or secondary schools, given their larger scale and ability to use waste heat efficiently. Because many large colleges and universities are equipped with large district cooling and heating facilities, the integration of CHP can be very cost effective.

The type of prime mover depends heavily on the electrical and thermal loads, ability to use the waste heat efficiently, and utility rates. Typically, schools are good candidates for gas-fired reciprocating engine prime movers or microturbine-based systems. Large universities can use reciprocating engine prime movers or gas-fired combustion turbines. Table 1 in Chapter 7 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment* provides information on the applicability of CHP.

Renewable Energy

The U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) (U.S. DOE 2014; http://www.energy.gov/eere) discusses several renewable energy (RE) options for schools, including solar, wind, and biomass.

Renewable energy utilization can add credits for USGBC LEED for Schools (USGBC 2009a), energy and atmosphere (credit 2) by awarding credits depending on the percentage of renewable energy used.

Given the increased number and popularity of solar systems in educational facilities, only these systems will be discussed in this chapter. Geothermal energy is also considered renewable; these systems are discussed earlier in this chapter and in Chapter 34.

Solar: Photovoltaic. Photovoltaic (PV) technology is the direct conversion of sunlight to electricity using semiconductor devices called solar cells. Photovoltaics are almost maintenance-free and seem to have a long lifespan. Their longevity, lack of pollution, simplicity, and minimal resource requirements make this technology highly sustainable, and, along with the proper financing mechanisms (as explained later), these systems can be economically justifiable.

Educational facilities are excellent candidate for PV technology due to the following reasons:

- Availability of large roof area
- Hours and seasons of operation
- Educational as a showcase of renewable energy technologies

The most common technology in use today is single-crystal PV, which uses silicon wafers wired together and attached to a module substrate. Thin-film PV, such as amorphous silicon technology, is based on depositing silicon and other chemicals directly on a substrate (e.g., 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 0.56 W/m^2 for thin films and up to 1.4 W/m^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 reliable storage batteries and an inverter increase the overall system cost. Barbose et al. (2013) found that the median installed price of PV systems completed in 2012 was $5.30/W for residential and small commercial systems smaller than 10 kW, and was $4.60/W for commercial systems of 100 kW or more.

The ability to transfer excess electricity generated by a photovoltaic system back into the utility grid can be advantageous for schools. 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 net metering: utilities pay and charge equal rates regardless of which way the electricity flows. School districts in these states will find PV more economically attractive. A good source of information on rebates and incentives for solar systems and other renewable technologies is the Database of State Incentives for Renewables & Efficiency [DSIRE (NCSU 2014), http://www.dsireusa.org], which is a comprehensive source of information on state, local, utility, and federal incentives and policies that promote renewable energy and energy efficiency.

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 should include sizing, analysis, economic analysis, design documents, specifications, permits, documentation for incentives, etc. The DSIRE database also provides state requirements for licensed solar contractors.

RETScreen® (Renewable Energy and Energy-Efficient Technologies) is a free decision support tool at http://www.retscreen.net, developed to assist in evaluation of energy production and savings, costs, emission reductions, financial viability, and risk for various types of renewable energy technologies (RETScreen 2014). The program is available in 35 languages.

In addition, several commercial tools are available for analysis of PV systems.

Financing PV projects in the educational sector can be more complex because of tax exemptions and questions of how to most efficiently allocate public funds and leverage incentives; detailed information can be found in Bolinger (2009) and Cory et al. (2008). The primary mechanism that has emerged to finance public-sector PV projects is a third-party ownership model. This model allows the public sector 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 in its property. The cost of the electrical power generated is then secured at a fixed rate, which is lower than the retail price for 15 to 25 years.

Figures 9 and 10 show examples of educational facilities' PV projects.

Solar: Thermal. Educational facilities can be good candidate for active thermal solar heating systems. In most cases, a solar hot-water system can reduce the energy required for service hot water and pool heating. Solar heating design and installation information can be found in ASHRAE (1988, 1991). Chapter 37 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment* and Krieth and Goswami (2007) are good sources of information for design and installation of active solar systems. Web-based sources include the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy's site at http://www.energy.gov/eere.

Value Engineering (VE) and Life-Cycle Cost Analysis (LCCA)

The use of value engineering (VE) and life-cycle cost analysis (LCCA) is growing in all types of construction and as part of the integrated design process (IDP) concept. In some cases, public facilities such as schools are required to use these procedures. Both

Fig. 9 Example of PV Installation at Ohlone College, Newark Center, Newark, CA: 450 kW, 3530 m^2
(Esberg 2010)

Fig. 10 Example of PV Installation at Twenhofel Middle School, Independence, KY: 22 kW
(Seibert 2010)

VE and LCCA are logical, structured, systematic processes used with decision support tools to achieve overall cost reduction, but there are some distinctions between them (Anderson et al. 2004).

In value engineering, 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 by modifying or eliminating nonessential design elements. Examples are using alternative systems or substituting equipment.

Life-cycle cost analysis is used to evaluate design alternatives (or alternative systems, equipment substitutions, etc., as part of VE) that meet the facility's 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 schools, because they are often government funded and intended for longer lifespans than commercial facilities. Unfortunately, VE and LCCA often are not included in the early design stages, 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. Therefore, VE and LCCA should be deployed in the early stages of the project. VE and LCCA programs for large schools can add 0.1 to 0.5% in initial cost, but can save 5 to 10% of initial costs and 0.5 to 10% of operation and maintenance costs (Dell'Isola 1997).

LCCA is recommended for economic evaluation as part of any school construction. 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 in account the time value of money. LCCA is more accurate: 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.

Chapter 37 provides details, tools, and examples of LCCA (refer to Table 7 in that chapter). Anderson et al. (2004) provides detailed information on all the aspects of design, construction management, cost control, and other resources for building and renovating schools.

The School as a Learning Tool for Sustainability

Schools are excellent for enhancing students' interest in energy efficiency and sustainable design from a young age. USGBC (2009a)'s LEED® for Schools awards one point for integrating high-performance features in the school curriculum (ID section, credit 3). Sources for this integration include the following:

- National Energy Education Development (NEED) project (http://www.need.org)
- Alliance to Save Energy's PowerSave Schools Program (http://ase.org/projects/powersave-schools)
- National Energy Foundation educational resources (http://www.nef1.org/)
- Energy Information Administration's Energy Kids web site (http://www.eia.gov/kids/index.cfm)

In addition, real-time feedback on how systems such as photovoltaic electrical generation, geothermal heat pumps, and water conservation save energy and operating costs is recommended. Seibert (2010) shows these features, as illustrated in Figure 11.

7. ENERGY DASHBOARDS

Energy dashboards provide information such as energy consumption, energy cost, EUI, CO_2 levels, or Energy Star rating. In some cases, the energy dashboard is part of an enterprise that incorporates features such as fault detection and diagnostics (FDD) tools, tracking of energy conservation projects, information-sharing tools, and other analytical features to enhance energy conservation. Educational facilities are good candidates for this system: for example, a school district can monitor and track the energy consumption of every school in the district in nearly real time. One good example is the Build Smart DC program (http://www.buildsmartdc.com/buildings/).

Features of Build Smart DC include the following:

- Tens of thousands of data points (15 min electricity data) delivered daily: annual energy consumption, annual energy cost, EUI, and Energy Star score
- Descriptions of energy efficiency projects ranging from low-cost building management system updates to full-scale school systems upgrades

Figure 12 depicts an example of the Build Smart DC energy dashboard for elementary and middle schools in Washington, D.C.

Figure 13 shows an example of higher education energy dashboard for a campus-scale facility with multiple buildings, where each individual building can be tracked, as shown in Figure 14.

Remember, however, that regardless of its sophistication, an energy dashboard will not save energy without action by site personnel (e.g., adjusting schedules or set points, fixing equipment malfunction).

8. COMMISSIONING

Commissioning (Cx) is a quality assurance process for buildings from predesign through design, construction, and operations. The commissioning process involves achieving, verifying, and documenting the performance of each system to meet the building's operational needs. Given the criticality of issues such as indoor air quality, thermal comfort, noise, etc., in educational 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 43 and ASHRAE *Guideline* 0-2005. Technical requirements for the commissioning process are described in detail in ASHRAE *Guideline* 1.1-2007; another useful source is from the AABC Commissioning Group (ACG 2005). Proper commissioning ensures that fully functional systems can be operated and maintained properly throughout the life of the building. Although commissioning activities should be implemented by a qualified commissioning professional or commissioning authority (CA), it is important for other professionals to understand the basic definitions and processes in commissioning.

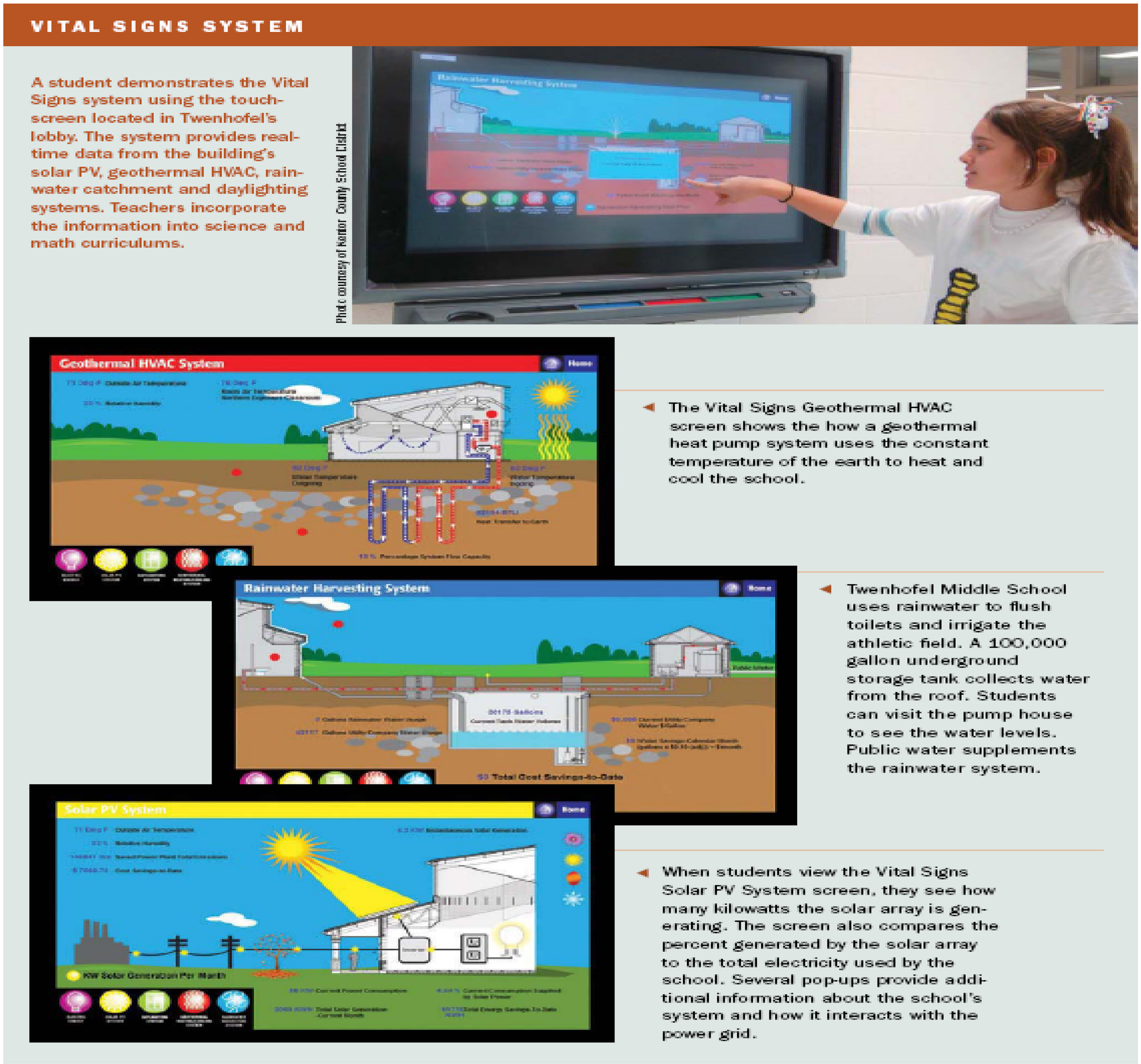
The following are basic terms used in commissioning:

- **Owner's project requirements (OPR):** a written document that details the functional requirements of the project and the expectations of how it will be used and operated.
- **Commissioning process:** 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:** an application of the commissioning process to a project that has been delivered using the commissioning process.
- **Retrocommissioning** (also called **existing building commissioning**): applied to an existing facility that was not previously commissioned.
- **Ongoing commissioning:** an extension of the commissioning process well into the occupancy and operation phase.

Commissioning: New Construction

Table 16 shows the phases of commissioning, as defined in ASHRAE *Guideline* 1.1-2007.

ACG (2005) refers to the following HVAC commissioning processes for new construction:



A student demonstrates the Vital Signs system using the touch-screen located in Twenhofel's lobby. The system provides real-time data from the building's solar PV, geothermal HVAC, rain-water catchment and daylighting systems. Teachers incorporate the information into science and math curriculums.

Photo courtesy of Kenton County School District

◄ The Vital Signs Geothermal HVAC screen shows the how a geothermal heat pump system uses the constant temperature of the earth to heat and cool the school.

◄ Twenhofel Middle School uses rainwater to flush toilets and irrigate the athletic field. A 100,000 gallon underground storage tank collects water from the roof. Students can visit the pump house to see the water levels. Public water supplements the rainwater system.

◄ When students view the Vital Signs Solar PV System screen, they see how many kilowatts the solar array is generating. The screen also compares the percent generated by the solar array to the total electricity used by the school. Several pop-ups provide additional information about the school's system and how it interacts with the power grid.

Fig. 11 Integration of Sustainability Features for Educational Purposes, Twenhofel Middle School, Independence, KY (http://www.twhvac.kenton.kyschools.us/)
(Seibert 2010)

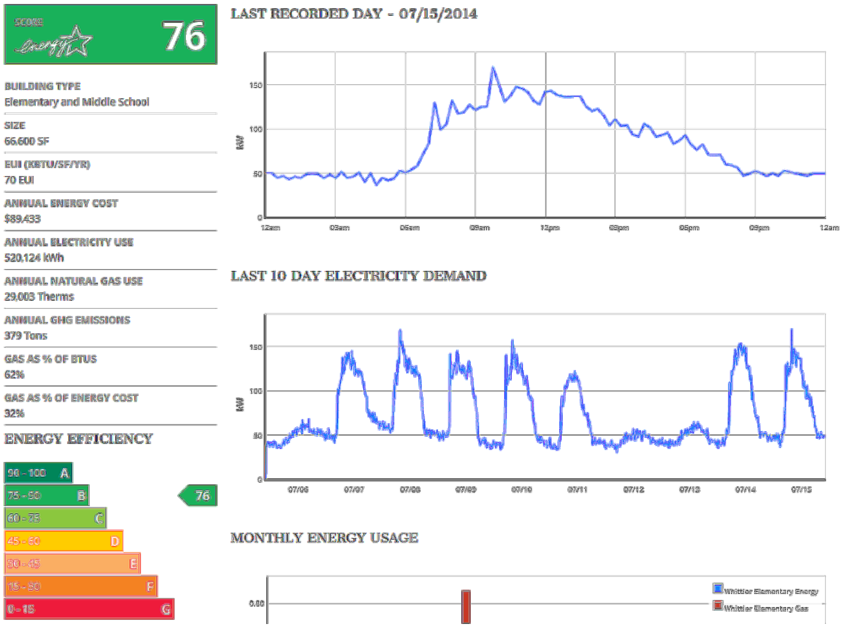
Table 16 Key Commissioning Activities for New Building

Phase	Key Commissioning Activities
Predesign	Preparatory phase in which 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.

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

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

Commissioning is an important element in new construction. LEED® for Schools (USGBC 2009a) requires as a prerequisite (Energy and Atmosphere, prerequisite 1) verification that the project's energy-related systems are installed and calibrated and perform according to the OPR, BOD, and construction document. Additional credits (Energy & Atmosphere, credit 3—Enhanced Commissioning) can be obtained by applying the entire commissioning process (or comprehensive HVAC commissioning), as described previously.



BUILDING TYPE
Elementary and Middle School

SIZE
66,600 SF

EUI (KBTU/SF/YR)
70 EUI

ANNUAL ENERGY COST
$89,433

ANNUAL ELECTRICITY USE
520,124 kWh

ANNUAL NATURAL GAS USE
29,003 Therms

ANNUAL GHG EMISSIONS
379 Tons

GAS AS % OF BTUS
62%

GAS AS % OF ENERGY COST
32%

Fig. 12 Building Smart DC Example for Whittier Elementary School, Washington D.C.
(http://www.buildsmartdc.com/building/58808/)

Table 17 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 Operation and maintenance (O&M) instruction and documentation Complete commissioning report

Source: ACG (2005).

Commissioning Existing Buildings

HVAC commissioning in existing buildings covers the following:

- Recommissioning
- Retrocommissioning (RCx)
- HVAC systems modifications

Although recommissioning and retrocommissioning differ, the methodology for both is identical. Retrocommissioning applies to buildings that were not previously commissioned. Recommissioning is initiated by the owner of a previously commissioned building, and seeks to resolve ongoing problems or to ensure that the systems continue to meet the facility's requirements. There also could have been changes in the building's occupancy, design strategies, equipment or equipment efficiency, occupant comfort, or IAQ that can initiate the need for recommissioning. Typical recommissioning activities are shown in Table 17.

Commissioning is also an important element in existing buildings. USGBC (2009b) *LEED® for Existing Buildings & Operation 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 modifications up to complete reconstruction of all or part of building's HVAC system. The process for this type of project should follow the process described previously for new construction.

9. SEISMIC- AND WIND-RESTRAINT CONSIDERATIONS

Seismic bracing of HVAC equipment should be considered. Wind restraint codes may also apply in areas where tornados 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 55 for further information.

10. SELECTED CASE STUDIES

Table 18 lists selected case studies of educational facilities as published in *ASHRAE Journal* from 2010.

In addition to the case studies mentioned in Table 18, ASHRAE's *High Performing Buildings* magazine provides many examples of high-performance educational facilities. These cases can be found in http://www.hpbmagazine.org/case-studies/educational.

REFERENCES

ACG. 2005. *ACG commissioning guideline*. AABC Commissioning Group, Washington, D.C.

AIHA. 2010. Laboratory ventilation. ANSI/AIHA *Standard* Z9.5-2012. American Industrial Hygiene Association, Fairfax, VA.

Anderson, D.R., J. Macaluso, D.J. Lewek, and B.C. Murphy. 2004. *Building and renovating schools: Design, construction management, cost control*. R.S. Means, Kingston, MA, and John Wiley & Sons, New York.

Table 18 Selected Case Studies from *ASHRAE Journal*

Project Name	Facility Type	Location	Description	Source
The Segundo Services Center (SSC) at University of California, Davis (UCD)	Higher Education	Davis, California	Student service center	A.K. Darwich: Holistic HVAC Design (April 2013)
Portland State University Academic and Student Recreation Center,	Higher Education	Portland, Oregon	Academic and student recreation center	M.O. Koller: PSU Design Build Project (May 2013)
City College of San Francisco	Higher Education	San Francisco, California	Classrooms, administrative offices, specialized laboratories, computer lab, study spaces, childcare/family training center, meeting rooms, café,	H. Janssens: Passive Cooling for School (May 2013)
Vancouver Island University (VIU)	Higher Education	Duncan, British Columbia, Canada	Classrooms, science labs, offices, meeting rooms and a cafeteria	L. Smith: Strategies for Sustainability (December 2013)
Université de Sherbrooke, Campus Longueuil	Higher Education	Longueuil, Québec, Canada	Classrooms, offices, labs, gathering areas, etc.	R. Dansereau: Bridging the Gaps (May 2012)
Maple School District, Northwestern High School	K -12	Maple, Wisconsin	Classrooms, labs, auditorium, gymnasium, and district offices	R. Thorson: Old School Learns Cool New Tricks (May 2012)
Jarvis Hall, The University of Wisconsin-Stout (UW-Stout)	Higher Education	Menonomie, Wisconsin	Labs, vivarium, clean rooms, classrooms, offices, and greenhouse	M.J. Lawless: Efficient Science Building (October 2012)
Ann Arbor Skyline High School	K-12	Ann Arbor, Michigan	Classrooms, learning communities, gymnasiums, cafeteria/commons, lab spaces, decentralized administration, auditorium, black-box theater, and natatorium	D.A. Crowe: State-of-Art School (May 2011)
St. Johns School	K-12	Saint-Jean-sur-Richelieu, Québec, Canada	Science rooms with laboratories and a library	J. Molia: Eco-Friendly, Affordable School (May 2011)
University of California, Merced, Sierra Terraces	Higher Education	Merced, California	Dormitory	G. Friedman: Energy-Saving Dorms (May 2010)
De Anza College, Kirsch Center for Environmental Studies	Higher Education	Cupertino, California	Classrooms, labs, open study stations	C. Roberts: Learning by Doing (May 2010)
The Kahnawake Survival School (KSS)	K-12	Kahnawake, Québec, Canada	High school, community center, public assembly	N. Lemire: School and More (May 2010)
Whitmore Lake High School	K-12	Whitmore Lake, Michigan	Gymnasium, cafeteria, natatorium, media center, commons area, and classrooms	R.N. Roop: Geothermal for School (May 2010)

*All articles are available from https://www.ashrae.org and with the online version of this chapter; ASHRAE members have free access to *ASHRAE Journal* articles via https://www.ashrae.org/resources--publications/ashrae-journal/ashrae-journal-members-only-redirect (must be logged in).

University of Massachusetts Energy Kiosk

How is Ag Engineering doing?

July 17,2014 01:36 pm

RT @UMass: #UMass #Amherst: M. Ice Hockey. Czepiel Returns To UMass As Director of Hockey Operations http://t.co/Ph3EyqinM8

Building sustainability on campus and beyond, a new football coach for UMass, an...

Fig. 13 Energy Kiosk Example for University of Massachusetts Amherst MA
(http://www.bedashboard.com/kiosk/20)

University of Massachusetts **Energy Kiosk**

How is **North Dorms** doing?

July 17,2014 01:43 pm

North Dorms

consumed last week:

62,293

kWh

RT @blackfemarch: Mrs. Elaine Gunn with the help of Chancellor Swamy and Director of Libraries, Jay Schaffer, cutting...

Fig. 14 Energy Kiosk Example for University of Massachusetts Amherst Tracking Specific Building on Campus
(http://www.bedashboard.com/Kiosk/Home/Index/20/174/rollover)

ANSI. 2010. Acoustical performance criteria, design requirements and guidelines for schools. *Standard* 12.60-2010. American National Standards Institute, Washington, D.C.

ASHRAE. 1988. *Active solar heating systems design manual*.

ASHRAE. 1991. *Active solar heating systems installation manual*.

ASHRAE. 2008. *30% advanced energy design guide for K-12 school buildings*. Available from https://www.ashrae.org/standards-research--technology/advanced-energy-design-guides/30-percent-aedg-free-download.

ASHRAE. 2010. *Thermal comfort tool*.

ASHRAE. 2011. *50% advanced energy design guide for K-12 school buildings*. Available from https://www.ashrae.org/standards-research--technology/advanced-energy-design-guides/50-percent-aedg-free-download.

ASHRAE. 2005. The commissioning process. *Guideline* 0-2005.

ASHRAE. 2007. HVAC&R technical requirements for the commissioning process. *Guideline* 1.1-2007.

ASHRAE. 2002. Measurement of energy and demand savings. *Guideline* 14-2002.

ASHRAE. 2008. Instrumentation for monitoring central chilled-water plant efficiency. *Guideline* 22-2008.

ASHRAE. 2012. Method of testing general ventilation air cleaning devices for removal efficiency by particle size. *Standard* 52.2-2012.

ASHRAE. 2013. Thermal environmental conditions for human occupancy. ANSI/ASHRAE *Standard* 55-2013.

ASHRAE. 2013. Ventilation for acceptable indoor air quality. ANSI/ASHRAE *Standard* 62.1-2013.

ASHRAE. 2013. Energy standard for buildings except low-rise residential buildings. ANSI/ASHRAE/IESNA *Standard* 90.1-2013.

ASHRAE. 2007. Standard method of test for the evaluation of building energy analysis computer programs. ANSI/ASHRAE *Standard* 140-2007.

ASHRAE. 2011. Standard for the design of high-performance green buildings except low-rise residential buildings. ANSI/ASHRAE/USGBC/IES *Standard* 189.1-2011.

Barbose, G., N. Darghouth, S. Weaver, and R. Wiser. 2013. Tracking the sun VI: An historical summary of the installed price of photovoltaics in the United States from 1998 to 2012, Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab).

BetterBricks. 2009. *Bottom-line thinking on energy in commercial buildings: Schools*. BetterBricks, Northwest Energy Efficiency Alliance, Portland, OR. http://www.betterbricks.com//schools.

Bolinger, M. 2009. Financing non-residential photovoltaic projects: Options and implications. Lawrence Berkeley National Laboratory *Report* LBNL-1410 E. Available from http://emp.lbl.gov/reports.

California Energy Commission. 2006. *Displacement ventilation design guide: K-12 schools*.

Chen, Q., and L. Glicksman. 2003. *System performance evaluation and design guidelines for displacement ventilation*. ASHRAE.

Cory, K., J. Coughlin, and C. Coggeshall. 2008. Solar photovoltaic financing: Deployment on public property by state and government. NREL Technical *Report* NREL/TP-670-43115, May 2009. Available at http://www.nrel.gov/docs/fy08osti/43115.pdf.

Dell'Isola, A.J. 1997. *Value engineering: Practical applications*. R.S. Means Company, Kingston, MA.

DiBerardinis, L.J., J.S Baum, M.W. First, G.T. Gatwood, and A.K. Seth. 2013. *Guidelines for laboratory design—Health and safety considerations*, 4th ed. Wiley, New York.

Ebbing, E., and W. Blazier, eds. 1998. *Application of manufacturers' sound data*. ASHRAE.

EPA. 2000. *Indoor air quality—Tools for schools*, 2nd ed. U.S. Environmental Protection Agency, Washington, D.C. http://www.epa.gov/iaq/schools.

EPA. 2010. *Laboratories for the 21st century (Labs21).* U.S. Environmental Protection Agency, Washington, D.C. http://www.epa.gov/lab21gov.

Esberg, G. 2010. Dispelling the cost myth. *High Performing Buildings* (Winter):30-42.

FEMP. 2008. *Measurement and Verification for Federal Energy Projects Version 3.0*, Federal Energy Management Program, Washington, D.C. http://www1.eere.energy.gov/femp/pdfs/mv_guidelines.pdf.

FEMP. 2010. *BLLC 5.3: Building life cycle cost program*. Federal Energy Management Program, Washington, D.C. http://www1.eere.energy.gov/femp/information/download_blcc.html.

Glazer, J. 2006. Evaluation of building performance rating protocols. ASHRAE Research Project RP-1286, *Final Report*.

Harriman, L.G., G.W. Brundrett, and R. Kittler. 2001. *Humidity control design guide for commercial and institutional buildings*. ASHRAE.

Kavanaugh, S.P., and K. Rafferty. 1997. *Ground-source heat pumps*. ASHRAE.

Krieth, F., and Y. Goswami. 2007. *Handbook of energy efficiency and renewable energy*. CRC Press, Boca Raton, FL.

Maor, I., and T.A. Reddy. 2008. Near-optimal scheduling control of combined heat and power systems for buildings, Appendix E. ASHRAE Research Project RP-1340, *Final Report*.

McIntosh, I.B.D., C.B. Dorgan, and C.E. Dorgan. 2001. *ASHRAE laboratory design guide*. ASHRAE.

Meckler, M., and L. Hyman. 2010. *Sustainable on-site CHP systems: Design, construction, and operations*. McGraw-Hill, Columbus, OH.

NCSU. 2014. *DSIRE database of state incentives for renewables & efficiency*. North Carolina State University, under National Renewable Energy Laboratory Subcontract XEU-0-99515-01. http://www.dsireusa.org/.

Neuman, D.J. 2003. *Building type basics for college and university facilities*. John Wiley & Sons, Hoboken, NJ.

New Buildings Institute. 2007. *Core performance guide: A prescriptive program to achieve significant, predictable energy savings in new commercial buildings*. New Buildings Institute, White Salmon, WA.

NRC. 1996. *Guide for the care and use of laboratory animals*. National Research Council, National Academy Press, Washington, D.C.

Orlando, J.A. 1996. *Cogeneration design guide*. ASHRAE.

Petchers, N. 2002. *Combined heating, cooling & power handbook: Technologies & applications*. Fairmont Press, Inc. Lilburn, GA.

RETScreen. 2014. *RETScreen® international: Empowering cleaner energy decisions*. Natural Resources Canada. http://www.retscreen.net/ang/home.php.

R.S. Means. 2015a. *Means mechanical cost data*. R.S. Means Company, Inc., Kingston, MA.

R.S. Means. 2015b. *Means maintenance and repair cost data*. R.S. Means Company, Inc., Kingston, MA.

Rumsey, P., and J. Weale. 2006. Chilled beams in labs. *ASHRAE Journal* 49(1):18-25.

Ryan, W. 2004. *Targeted CHP outreach in selected sectors of the commercial market*. Report prepared by the University of Illinois at Chicago Energy Resource Center for the U.S. Department of Energy, Energy Efficiency and Renewable Energy Program.

Schaffer, M.E. 1993. *A practical guide to noise and vibration control for HVAC systems*. ASHRAE.

Siebein, G.W., and R.M. Likendey. 2004. Acoustical case studies of HVAC systems in schools. *ASHRAE Journal* 46(5):35-47.

Siebert, K.L. 2010. An energy education. *High Performing Buildings* (Winter):44-55.

Skistad, H., E. Mundt, P.V. Nielsen, K. Hagstrom, and J. Railio. 2002. *Displacement ventilation in non-industrial premises*. Federation of European Heating and Air-Conditioning Associations (REHVA), Brussels.

USGBC. 2009a. *LEED® 2009 for schools—New construction and major renovations*. U.S. Green Building Council, Washington, D.C. Available from http://www.usgbc.org/resources/leed-schools-new-construction-v2009-current-version.

USGBC 2009b. *LEED® 2009 for existing buildings and operation maintenance*. U.S. Green Building Council, Washington, D.C. Available from http://www.usgbc.org/resources/leed-existing-buildings-operations-amp-maintenance-recertification-guidance.

U.S. DOE. 2009. *EnergySmart schools*. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Available at http://energy.gov/sites/prod/files/2013/11/f5/ess_o-and-m-guide.pdf.

U.S. DOE. 2014. *Office of Energy Efficiency and Renewable Energy (EERE)*. U.S. Department of Energy, Washington, D.C. http://www.energy.gov/eere.

Wright, G. 2003. The ABC's of K-12. *Building Design & Construction*, June.

BIBLIOGRAPHY

ASHRAE. 2013. *Standard 90.1-2013 user's manual*.

ASHRAE. 2010. *ASHRAE greenguide: The design, construction and operation of sustainable buildings*, 3rd ed. J.M. Swift and T. Lawrence, eds.

ASHRAE. 2006. Weather data for building design standards. ANSI/ASHRAE *Standard* 169-2006.

CHPS. 2010. *Best practices manual*. Collaborative for High Performance Schools, CA. Available from http://www.chps.net/dev/Drupal/node/288.

Darbeau, M. 2003. ARI's views on ANSI S-12.60-2002. *ASHRAE Journal* 45(2):27.

Harriman, L.G., and J. Judge. 2002. Dehumidification equipment advances. *ASHRAE Journal* 44(8):22-27.

Lilly, J.G. 2000. Understanding the problem: Noise in the classroom. *ASHRAE Journal* 42(2):21-26.

Megerson, J.E., and C.R. Lawson. 2008. Underfloor for schools. *ASHRAE Journal* 50(5):28-30, 32.

Moxley, R.W. 2003. Prioritizing for preschoolers. *American School & University* (November).

Mumma, S.A. 2001. Designing dedicated outdoor air systems. *ASHRAE Journal* 43(5):28-31.

Nasis, R.W., and R. Tola. 2002. Environmental impact. *American School & University* (November).

Nelson, P.B. 2003. Sound in the classroom—Why children need quiet. *ASHRAE Journal* 45(2):22-25.

Perkins, B. 2001. *Building type basics for elementary and secondary schools*. John Wiley & Sons, New York.

Schaffer, M.E. 2003. ANSI standard: Complying with background noise limits. *ASHRAE Journal* 45(2):26.

U.S. DOE. 2002. *National best practices manual for building high performance schools*. U.S. Department of Energy, Washington, D.C. Available from http://www.epa.gov/iaq/schools/high_performance.html.

Watch, D. 2001. *Building type basics for research laboratories*. John Wiley & Sons, New York.

Wolf, M., and J. Smith. 2009. Optimizing dedicated outdoor-air systems. *HPAC Engineering* (December).

Wulfinghoff, D.R. 2000. *Energy efficiency manual*. Energy Institute, Wheaton, MD.

Related Commercial Resources