11

Heat, Ventilation and Air Conditioning (HVAC)

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Heating, ventilation and air conditioning (HVAC) systems are responsible for meeting the requirements of an indoor environment, with regard to air temperature, humidity and air quality by heating or cooling the spaces. HVAC systems represent an important part of the energy needs in industry and building sectors as it has been shown that such systems consume most of the energy in buildings, requiring almost 50% of the total energy demand [1].

HVAC systems are part of an energy chain for conditioning a space using different energy sources and converting them into thermal energy to meet the required level of comfort (see Figure 11.1). HVAC systems use fuels and electricity; fossil fuels are the most common source for heating whereas electricity is the almost the only source for cooling. Apart from cooling, electricity is also used to move fluids to enable thermal energy to reach the required spaces.

Fans and pumps used in thermal generation and transportation processes are the main electric energy consumers in an HVAC system. These are driven by electric motors and their energy efficiency is related to the use of power electronics-based drives, a topic that is principally covered in Chapter 9. Apart from optimizing the consumption of these electrical devices, there is a great potential for energy savings in order to decrease the energy consumption of HVAC systems as a whole, as well as in heat and cold generators. This can be achieved by reducing the thermal energy demand by passive methods and the use of renewable energy sources to support the production of both heat and cold. This chapter deals mainly with energy saving measures to reduce the thermal energy demand in HVAC systems and, as a consequence, achieve higher energy efficiency ratios.

Heat transfer is the basis of the performance of an HVAC system in order to heat or cool a space. This transference is performed in a set of heat exchangers (evaporators and condensers) that can be on their own or a part of a cool or heat generation device. Heat exchange processes are studied using thermodynamics.

Electrical Energy Efficiency: Technologies and Applications, First Edition. Andreas Sumper and Angelo Baggini.

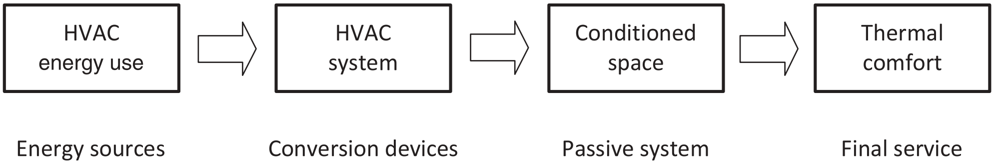

Figure 11.1 The map of energy flow to deliver thermal comfort [2]

In this chapter, first the basic concepts of thermodynamics with regard to HVAC systems are reviewed, with a special focus on cooling. HVAC systems are used in a variety of activities and places, so the thermal needs differ from one application to another. Secondly, the parameters used for defining indoor conditions are described.

HVAC systems consist of a set of equipment, a distribution network and terminals for delivering thermal energy to condition a space either collectively or individually. The interaction of these during their performance makes an assessment of the energy balance a complex task. Thirdly, the most common HVAC systems are described and the energy conversions involved are analysed.

Lastly, energy efficiency measures are listed for each link of the energy flow presented in Figure 11.1. Most of such measures are focused on decreasing energy demand, that is, thermal demand, which leads to a general reduction in the consumption of energy.

11.1 Basic Concepts

It is well known that heat flows naturally from a hot area to a cold one. Such heat transfer does not require the use of energy. So heat exchangers, evaporators and condensers are simple devices that normally consist of two fluids at different temperatures that flow through two different circuits. The hotter fluid transfers its heat to the colder fluid. After such a transfer, the hot fluid loses temperature and the cold one increases its temperature.

However, the reverse process it is not possible by itself: it needs the use of a thermal engine called a refrigerator. Thermal engines are, generally speaking, devices that have a cyclic operation, removing heat from one region and injecting it into another. A fluid (called a refrigerant) is normally used as the medium to transfer such heat during its cycle.

Refrigerators work as shown in Figure 11.2(a) for a vapour-compression process. The fluid (refrigerant) enters the compressor as vapour and is compressed up to condenser pressure, achieving a high temperature. When it flows through the condenser, it cools and condenses as it delivers its heat to the hot environment. It then reaches the expansion valve where both its pressure and temperature fall drastically due to the throttle effect. At this low temperature, it enters the evaporator and evaporates, absorbing heat from the space to be refrigerated. The cycle is completed when the fluid leaves the evaporator and flows into the compressor again.

The objective of a refrigerator is to eliminate heat, Q_L, from a refrigerated space. In order to achieve this, it requires external work, W_net. The efficiency of a refrigerator is expressed in terms of the coefficient of performance (COP), which is the ratio of useful heat movement to

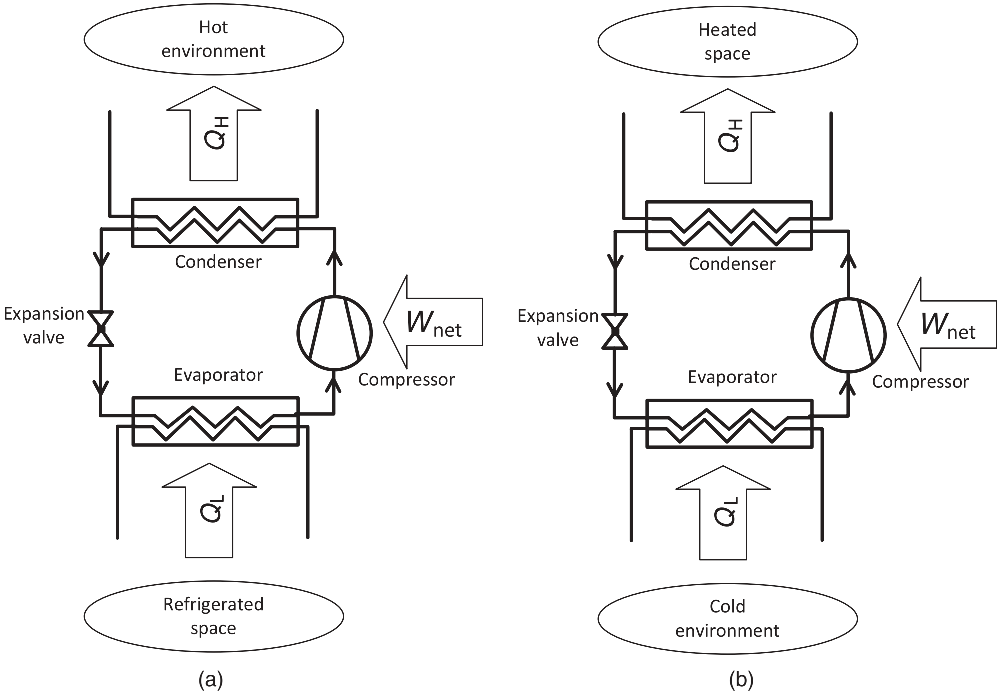

Figure 11.2 (a) Refrigerator and (b) heat pump

work input (equation (11.1)). The work input corresponds to the consumption of the electrically powered pumps.

$$COP_{\mathrm{refrigeration}} = \frac{Q_{\mathrm{L}}}{W_{\mathrm{net}}}. \tag{11.1}$$

The work capability of refrigerators is expressed in terms of $COP_{\mathrm{refrigeration}}$ to avoid confusion, since it can have a value greater than unity as the heat removed from the refrigerated space can be greater than the work input.

The heat pump is another device that uses the same cycle as a refrigerator and can transfer heat from an area with low temperature to another area with high temperature (see Figure 11.2(b)). Nevertheless, the aim of a heat pump is to keep a space heated. This goal is achieved by absorbing heat from a cold environment and delivering that heat to the required space.

The work capacity of a heat pump is also expressed by the coefficient of performance according to equation (11.2). It can also have values greater than unity. A typical value of COP_{heating} is between 2 and 3. The COP_{heating} falls below 1 if the temperature of the cold environment is too low. In such a case, the heat pump changes its operation mode to electric heating.

$$COP_{\mathrm{heating}} = \frac{Q_{\mathrm{H}}}{W_{\mathrm{net}}}. \tag{11.2}$$

Modern heat pumps are equipped with a suitable control and a reversal valve, so they can provide heat in the winter and work as a refrigerator in the summer. For additional information on the thermodynamics involved the reader is referred to [3].

11.2 Environmental Thermal Comfort

The energy consumption of a building depends significantly on the demands of the indoor environment, which also affects health, performance and the comfort of the occupants. It is commonly estimated that people in economically developed countries spend at least 80% of their time indoors (at home, at work, at school or when commuting). This suggests that the Indoor Environmental Quality (IEQ) can have a significant impact on people, as well as on the energy consumption for heating and cooling purposes. In an effort to maintain the quality of the indoor environment, buildings are mechanically conditioned to provide constant, uniform, ‘comfortable’ environments. Recent revisions of international standards have updated the definitions of comfort and the ways to use them in designing and evaluating buildings. These revisions are based on research field studies carried out around the world that have shown that the so-called adaptive approach describes comfort conditions in non-air-conditioned buildings better. There are differences in the adaptive approach that have relevant implications on ways of designing, constructing and operating buildings, especially if low-energy buildings and Net Zero Energy Buildings (NZEBs) are the objectives. NZEBs are grid-connected high-performance buildings that annually produce energy from on-site renewable sources, which compensates for the annual energy consumption. Nevertheless, if the rationale is to endorse the design of environmentally friendly buildings that promote sustainable development, then reasonably strict requirements on energy efficiency should be satisfied while providing high levels of IEQ.

IEQ should address four aspects: indoor air quality, thermal environment, lighting and acoustics. All of these are related and have their effects on health, comfort and performance. ‘Health’ is understood very broadly as the state of complete physical, mental and social well-being and not merely the absence of disease. ‘Comfort’ expresses satisfaction with the environment. ‘Performance’, or productivity, is related to the ability to perform demanding tasks. Health, comfort and productivity can be influenced by physiological, behavioural factors or social and organizational variables, not only by IEQ conditions. Although light and noise are important constituents of IEQ, they will not be treated in depth here.

The most important variables that affect thermal comfort are the air temperature, the mean radiant temperature, the relative air velocity, the relative humidity (or the water content in the air), the type of activity undergone by people (which determines the heat production in the body) and their clothing (which offers thermal resistance to the heat transfer between the human body and the environment). Research conducted mainly during the 1970s by Fanger [4] in well-controlled environments has been partially taken and reorganized into international standards where thermal comfort is defined as ‘that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation’.

Thermal conditions affect health. This is illustrated by the mortality rates during extremely hot weather conditions. In the case of less extreme conditions, elevated temperatures have been associated with the increased prevalence of symptoms typical of sick-building syndrome

(SBS) and several studies indicate that it is beneficial to keep the temperatures in buildings at the lower level of thermal comfort.

Thermal conditions can affect the performance or work through several mechanisms. An unpleasant sensation of being too hot or too cold (thermal discomfort) can distract people from their work and disturb their feelings of wellbeing. This may lead to reduced concentration and decreased motivation to work. The consequence of such a state is usually a reduction of productivity. Seppanen *et al*. (2006) [5] showed that performance increased with temperatures up to 20–23°C and decreased with temperature above 23–24°C. Maximum performance was predicted to occur at a temperature of 21.6°C. The data were obtained in office environments, factories, field laboratories and school classrooms. Nevertheless, other studies and surveys show that people accept a wider temperature and humidity swing if they can influence their own environment, especially with operable windows [6]. Recent projects such as the ThermoCo Project [7] analysed user satisfaction in buildings with regards to the upper temperature limits of the adaptive comfort model, showing the need for further scale surveys, particularly in hot (European) climates.

IAQ (Indoor Air Quality) is an important parameter that characterizes the indoor environment and is strongly related to the health of a building's occupants. The quality of indoor air can be defined as the level of the contaminants/pollutants in indoor air. The operation and the performance of the ventilation system directly determine the IAQ of an indoor space. In addition, the air flow and paths inside the building have an important influence on the thermal comfort of the occupants, especially during the summer. It is known that slight air velocities up to 1.5 m/s improve thermal comfort for moderate activities.

So the impact of thermal comfort expectations and the impact of ventilation on the energy performance of a building is crucial. When the outdoor fresh air supply is increased, the cooling and heating energy requirements are also increased when the cooling or heating system is in operation. On the other hand, there are energy conservation strategies, such as free cooling operation and the use of natural ventilation in buildings, which becomes much easier when indoor temperature comforts are applied as a consequence of an adaptive approach.

The results of recent research works have shown that when variable indoor temperatures comfort standards based on adaptive theory are used, remarkable energy savings may occur [8]. Savings of up to 18% or up to 34% in residential buildings in a Mediterranean climate may be achievable.

The most recent standards to specify the combination of indoor thermal environmental factors and personal factors that will produce thermal environmental conditions that are acceptable to a majority of the occupants are ANSI/ASHRAE Standard 55-2010 and EN-15251-2007. Both standards propose that acceptable temperature ranges actually depend on the type of system used to provide comfort. The European standard EN-15251 specifies the parameters for design addressing indoor air quality, lighting and acoustics, not just the thermal environment.

Standard AHSRAE 62.1 is used for determining the minimum ventilation requirements for high-performance buildings. The minimum air exchange ratio of fresh air is defined as a function of the occupation density and the surface of the conditioned area. Table 11.1 illustrates as an example of such ratios.

The required ventilation will be the result of the addition of the two requirements. The standard allows changes in the quantity of fresh air needed depending on the level of occupancy or other operational conditions.

Table 11.1 Air-exchange ratio requirements in buildings

Type	Requirement per person [l/s person]	Requirement per surface [l/s m^2]
Offices	2.5	0.3
Residential	2.5	0.3
Classrooms	3.8	0.3
Restaurants	3.8	0.9

According to EN-15251, several criteria are used for the definition of the fresh air ratios. Two of them are aligned with the method described in ASHRAE 62.1 and considers both the ventilation needed to dilute the pollutants emitted by the occupants and the building. The standard classifies the buildings into three categories (I, II, III), depending of the percentage of dissatisfied persons. Table 11.2 gives the recommended values for the three categories.

With regard to the control of the ventilation systems, in periods when the building is not occupied by people, the ventilation can be reduced to minimum values (0.1–0.2 l/s m^2 in non-residential buildings, 0.05–0.1 l/s m^2 in residential buildings).

With regard to thermal comfort, which drives the design of heating and cooling systems, EN-15251 distinguishes the buildings that are provided with mechanical cooling systems from those without. For buildings provided with mechanical air-conditioning systems, the criteria for determining thermal comfort are based on the method of Fanger and on the PMV–PPD (Predicted Mean Vote–Percentage of People Dissatisfied) indexes. ASHRAE 55 made a similar distinction and recommends the ranges for typical applications to be PPD < 10 and PMV ($-0.5 <$ PMV < 0.5). The values of the indexes are shown in Table 11.3.

EN 15251 allows the use of an adaptive model for buildings without mechanical cooling. In the definition section, 'buildings without mechanical cooling' are defined in the standard as 'buildings that do not have any mechanical cooling and rely on other techniques to reduce high indoor temperature during the warm season like moderately-sized windows, adequate sun shielding, use of building mass, natural ventilation, night time ventilation etc. for preventing overheating'. Mechanical cooling is defined as 'cooling of the indoor environment by mechanical means used to provide cooling of supply air, fan coil units, cooled surfaces, etc.'. The adaptive model can be applied to spaces equipped with operable windows that open to the outdoors and that can be readily opened and adjusted by the occupants of the spaces. There shall be no mechanical cooling in operation in the space. Mechanical ventilation with

Table 11.2 Recommended values for obtaining fresh air according to EN-15251

Category	Air flow by person [l/s person]	Air flow per surface [l/s m^2]		
		Very low polluted building	Low polluted building	Polluted building
I	10	0.5	1	2
II	7	0.35	0.7	1.4
III	4	0.2	0.4	0.8

Table 11.3 Values of PPD and PMV indexes for thermal comfort

Category	PPD	PMV
ASHARE 55	<10	$-0.5 < \text{PMV} < 0.5$
EN-15251-I	<6	$-0.2 < \text{PMV} < 0.2$
EN-15251-II	<10	$-0.5 < \text{PMV} < 0.5$
EN-15251-III	<15	$-0.7 < \text{PMV} < 0.7$

unconditioned air (in summer) may be used, but opening and closing of windows shall be of primary importance as a means of regulating thermal conditions in the space. There may, in addition, be other low-energy methods of personally controlling the indoor environment such as fans, shutters, night ventilation, etc.

ASHRAE Standard 55 makes a similar distinction but does not have exactly the same wording, allowing the application of an adaptive model (based on outdoor monthly average temperatures), in 'occupant-controlled naturally conditioned spaces' defined as 'those spaces where the thermal conditions of the space are regulated primarily by the occupants through opening and closing of windows'.

In general, the application of the adaptive model indicates that indoor thermal comfort is achieved with a wider range of temperatures than by implementation of the Fanger model. The temperature limits shown in Figure 11.3 for EN 15251 should be used for dimensioning

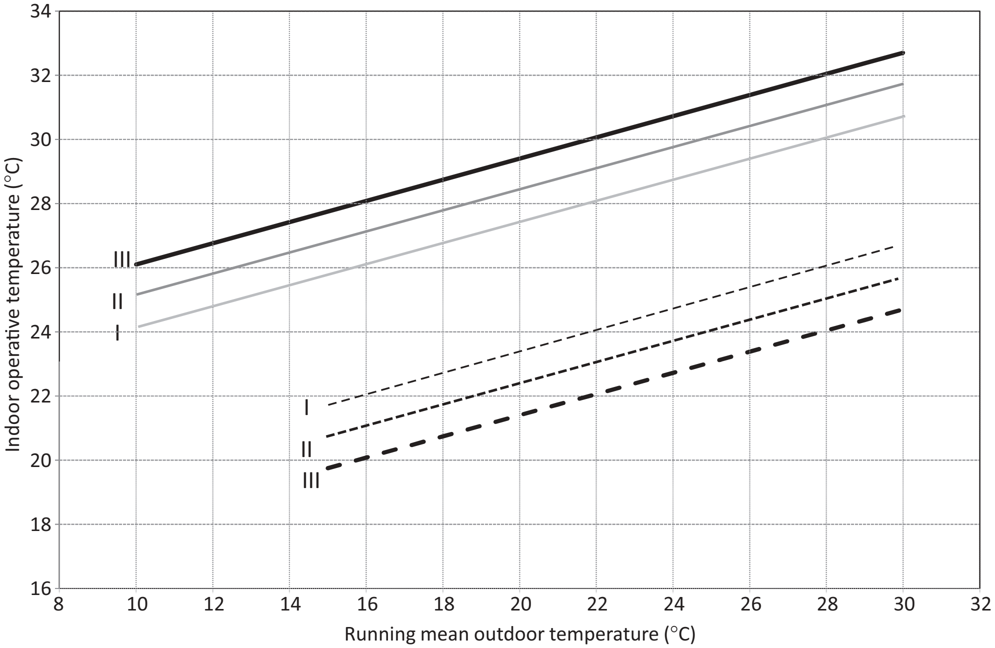

Figure 11.3 Acceptable indoor operative temperature ranges (cooling season) for buildings without a mechanical cooling system as a function of outdoor air daily running mean temperature (from EN 15251)

the passive means of preventing overheating in summer and are function of the mean ambient temperature. When the adaptive temperature limits (upper limits) cannot be guaranteed by passive means, the design criteria for buildings with mechanical cooling should be used. In [5] it is shown that using some of the indexes proposed by EN 15251 and their intended use (start with its adaptive variant and, if comfort conditions for the chosen category cannot be met, switch to the Fanger variant) implies the presence of discontinuities in the procedure. This is because with common assumptions on metabolic rate and clothing certain conditions will be above the comfort range for Fanger and below the range for adaptive.

11.3 HVAC Systems

The service of HVAC systems covers air circulation, control of temperature and the control of humidity. The needs of ventilation and air conditioning vary widely depending on the requirements of the indoor environment. Consequently, there is a variety of HVAC systems. Depending on their capability to provide such services, HVAC can be classified into five service levels (Table 11.4).

HVAC systems contain a large variety of components that include equipment for generating heat and cool, air-handling units (AHU), distribution networks and terminals. The more services that are demanded, the more complex the system will be.

Heating technologies comprise boilers, furnaces and unit heaters, which typically use fossil fuels. Cooling technologies include chillers, cooling towers and air conditioning equipment, which usually consume electricity. Compression systems using gas or other cooling systems such as absorption chillers, adsorption chillers or desiccant systems are alternatives to electric chillers. Distribution networks include air-handling units, fans and pumps, which mainly consume electricity.

The most common HVAC systems for buildings are all-air and all-water systems and are described next. A wider overview of such systems can be found in [9].

All-air systems are habitually used when cool generation is mainly required. Figure 11.4 shows a common arrangement of components of an all-air system with a boiler as a generator of heat and a water-cooled chiller connected to a cooling tower as a generator of cool. In such systems, outdoor air enters the AHU, which includes a fan, filters to clean the air, coils for heating or cooling the air that passes through them, and humidifiers (if required). After going through the AHU, the conditioned air is delivered to the spaces by a network of supply air ducts and a parallel network of return air ducts transports exhausted air.

Table 11.4 Classification of thermal comfort service quality [1]

Service level	Ventilation	Heating	Cooling	Humidification	Dehumidification
SL0	√				
SL1	√	√			
SL2	√		√		
SL3	√	√	√		
SL4	√	√	√	√	
SL5	√	√	√	√	√

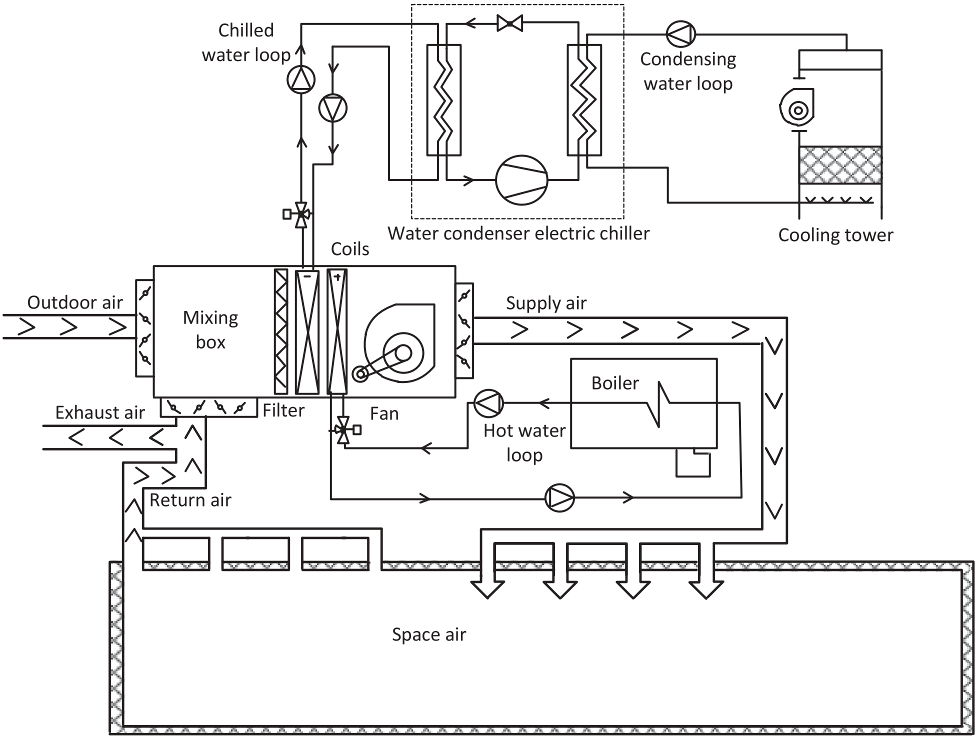

Figure 11.4 Elements of typical all-air HVAC system with chilled and hot water generation

The majority of all-air systems have a single duct system that provides either heat or cool to the conditioned spaces. HVAC single duct systems can be divided into the following:

- Single zone systems are the simplest all-air system as they deliver a constant volume of air with the same temperature to the entire facility. They are commonly used, for example, in department stores, factory spaces and auditoriums.
- Variable air volume (VAV) systems permit one to control the temperature individually in separate zones. They are widely used in large buildings.
- Reheating is achieved by adding coils to both former systems to allow conditioning individually in each zone. They are used in spaces with precise humidity requirements such as museums and some industrial processes.
- Multizone systems have a dedicated duct directly connected with the AHU that supplies conditioned air independently to each zone. They are almost obsolete except in small buildings with few zones and short duct distances.

Apart from widespread single duct systems, there are dual duct systems that have separate ducts for heating and cooling purposes. Both distribution networks run in parallel and the air is mixed in mixing boxes in each zone. They are used in buildings with strict requirements for temperature and humidity. HVAC dual duct systems can be divided into constant air volume (CAV) systems and variable air volume (VAV) systems.

Water, in its different stages, is more appropriate than air for transporting heat energy in both heating and cooling systems. However, the humidity, which affects air quality, cannot be controlled. Water distribution piping systems can be formed by one pipe, by connecting all terminals units in a loop; by two pipes, one to supply each terminal unit and the other for the return; three pipes, one supply of heated water, the other for chilled water and the last for a common return; and even by four pipes, supply and return pipes from terminal units for both heating and cooling. All-water HVAC systems can be divided into the following categories:

- Natural convection is the simplest all-water HVAC system. It uses hydronic convectors.
- Radiant heating systems can employ electric resistance heating or combustion as a heat source. Low temperature systems can be installed in floors, while medium temperature systems are panel mounted.
- Fan-coils systems are small air-handling units for a single space with a coil connected to a supply of hot and/or chilled water. A fan blows air through the coil to condition the space. If it has an outside inlet, it is called a unit ventilator.

All the systems that have been described are normally classified as central air-conditioning systems as the generation of heat and cool is centralized. Such systems are useful for large buildings. However, smaller systems can be used for the same purposes, although there is a limit to their area of influence. Heat pumps are an example of packaged terminal air-conditioners that can deliver heat and cool. In contrast, there are unit heaters that are only able to deliver heat, such as fan-forced unit heaters and high temperature infrared heaters.

11.3.1 Energy Conversion

HVAC systems consist of a huge number of interconnected elements and subsystems that make a global assessment of the energy conversion procedures complex. The representation of the energy conversion processes by HVAC loops [1, 10] facilitates the identification of such processes by assessing the energy involved in each transformation and then the energy balance.

Figures 11.5 and 11.6 represent the all-air HVAC system shown in Figure 11.4 through HVAC loops. Figure 11.5 (a) depicts the thermal energy chain in heating mode via three loops (if boiler is used):

- Combustion loop: heat is generated in the boiler by burning fuel.
- Hot water loop: water is heated in the boiler and is cooled in the coil; water is driven by pumps.
- Air loop: heat is delivered to the conditioned space; air is driven by fans.

Figure 11.5(b) also illustrates the energy chain in heating mode via four loops (if a heat pump is used). In this case they are as follows:

- Heat extraction loop: heat is extracted from the environment to the evaporator. Air is driven by fans.
- Refrigerant loop: the refrigerant works on a vapour-compression cycle extracting heat from the evaporator and transfer it to condensing water. The refrigerant is driven by a compressor.

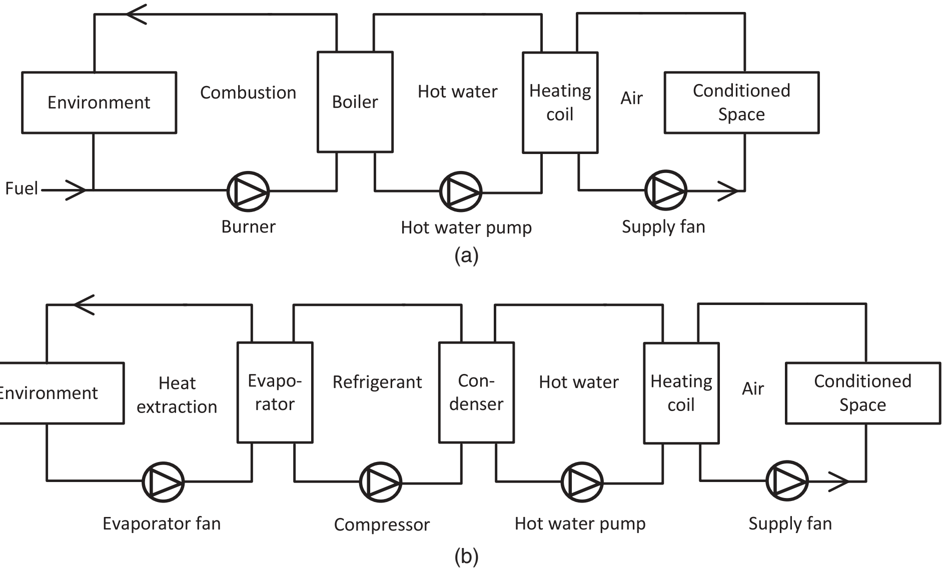

Figure 11.5 HVAC thermal chain for heating: (a) hot water boiler; (b) air to water heat pump

- Hot water loop: water is heated in the condenser and is cooled in the heating coil. Water is driven by pumps.
- Heat extraction loop: heat from the heating coil is delivered to the conditioned space. The air is driven by fans.

Figure 11.6 shows the cooling mode via five loops:

- Air loop: heat is extracted from the conditioned space to the chilled water. Fans drive air through the ducts and then it passes through cooling coils to produce heat transfer.
- Chilled water loop: chilled water is heated in the cooling coils and it is cooled in the chiller evaporator. The chilled water is driven by pumps.
- Refrigerant loop: the refrigerant works on a vapour-compression cycle extracting heat from the evaporator and transferring it to the condensing water. The refrigerant is driven by a compressor.
- Condensing water loop: heat from the condenser is transported to the cooling tower. The water is driven by pumps.
- Heat rejection loop: heat is ejected to the environment in the cooling tower.

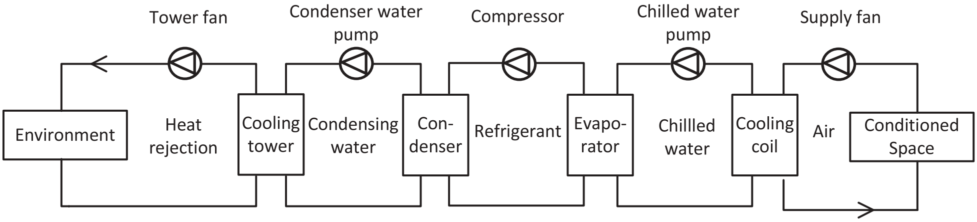

Figure 11.6 HVAC thermal chain for cooling

In HVAC systems, fluid movers (pumps and fans) and heat/cool generators (chillers, boilers, heat pumps, furnaces, etc.), needs energy to work. However, heat exchanging devices, which link thermal loops (water coils, evaporators and condensers), do not consume any energy since the heat transference is due to a temperature difference.

11.3.2 Energy Balance

An HVAC system normally consists of four main subsystems: heat generation, cold generation, water transportation, and air transportation. Figure 11.7 shows the energy balance between such subsystems, where Q refers to thermal load, L refers to power losses, and C means consumption [1].

Heat generation (HG) uses energy from an external source (C_{HG}) with the aim of adding heat to water (Q_{HG}) or to air (usually through coils (Q_{COIL})). In boilers and furnaces energy losses (L_{HG}) can result from unburned fuel, vent gases and through the walls. In heat pumps, such losses denote the energy absorbed from the environment in the evaporator. Then, the energy balance in this subsystem is: $C_{\mathrm{HG}} = Q_{\mathrm{HG}} + L_{\mathrm{HG}}$.

Cold generation (CG) needs the consumption of energy (C_{CG}) for removing heat (Q_{CG}) from water or air (usually through coils (Q_{COIL})) transportation subsystems. The energy losses (L_{CG}) are the energy rejected to the environment by the cooling subsystem, including pumps and fans that are used in refrigerant compression, air-cooled devices and water-cooled devices. Then, the energy balance in this subsystem is: $C_{\mathrm{CG}} = Q_{\mathrm{CG}} + L_{\mathrm{CG}}$.

A water transportation (WT) subsystem uses energy from an external source (C_{WT}) for feeding pumps that drive water from the generation equipment to the water coils through pipes. Heat exchange between generation subsystems and water is known as primary load (Q_{PRI}). If it is positive it means heat generation and if it is negative it means cold generation. The energy losses (L_{WT}) are caused by inefficiencies in the pumping process, water escape and thermal losses in the water distribution network. Then, the energy balance for this subsystem is: $Q_{\mathrm{PRI}} = Q_{\mathrm{COIL}} + L_{\mathrm{WT}} - C_{\mathrm{WT}}$.

An air transportation (AT) subsystem uses energy from an external source (C_{AT}) for feeding fans that drive conditioned air (Q_{SP}) from the water coils to the conditioned space through air

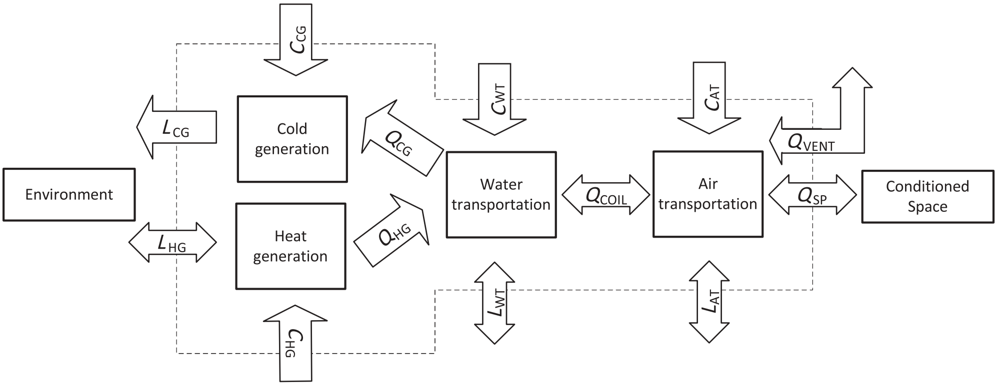

Figure 11.7 Energy balance in HVAC subsystems

ducts. Fans are also used for ventilation that considers the energy contained in return air and exhaust air (Q_{VEN}). The energy losses (L_{AT}) are produced by inefficiencies in fans, air leaks or infiltrations, and thermal losses in the air distribution network. Then, the energy balance for this subsystem is: $Q_{\mathrm{COIL}} = Q_{\mathrm{SP}} + Q_{\mathrm{VEN}} - C_{\mathrm{AT}} + L_{\mathrm{AT}}$.

11.3.3 Energy Efficiency

The final energy consumption of an HVAC system depends on the building in which it is placed, the environmental parameters considered at the design stage, the equipment installed, the leaks and infiltrations in fluid transportation subsystems, and the operating controls established according to building requirements, among other factors.

Therefore, the energy efficiency of such a system varies widely depending on the service it provides. Moreover, it is rather difficult to establish one energy efficiency index in order to compare its performance with other systems. The comparison of HVAC systems is easily made by means of relative energy efficiency.

The relative energy efficiency of the air conditioning systems mentioned in this chapter is shown in Figure 11.8. It can be seen that CAV dual duct HVAC systems are comparatively less efficient than the rest of the HVAC systems. On the other hand, individual units, heat pumps

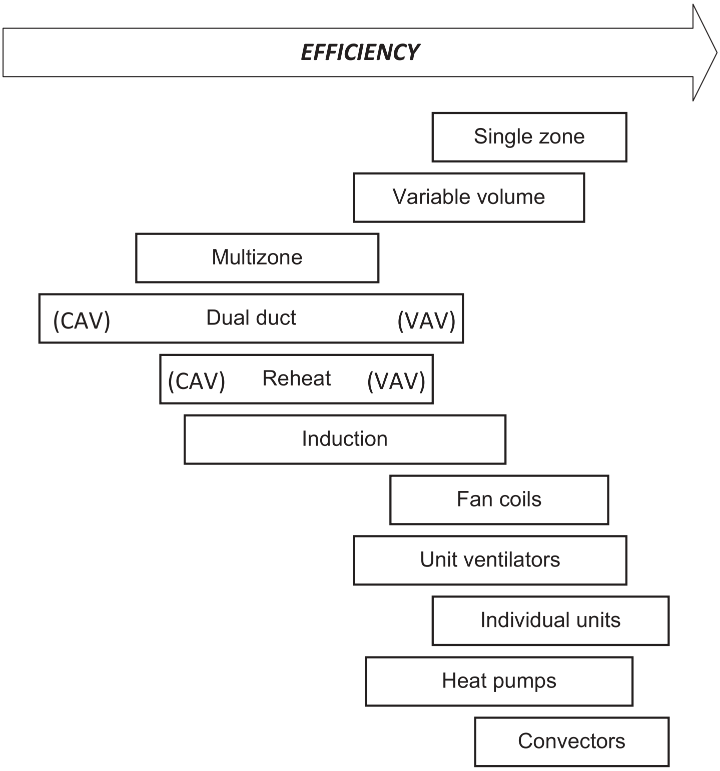

Figure 11.8 Relative energy efficiency of HVAC systems [11]

and convectors are comparatively the most efficient HVAC systems. The most appropriate system for each application can be consulted in [9].

11.4 Energy Measures in HVAC Systems

The energy efficiency in HVAC systems can be handled at each of the stages of the HVAC energy chain (Figure 11.1). It can be improved by focusing on the specific technical components in each component of the chain:

- *Final service*: Establishing limits on both ventilation rates and indoor comfort conditions through HVAC energy policies in order to encourage a rational use of energy.
- *Passive system*: Designing envelopes using high insulation, good air tightness and heat recovery ventilation systems in order to meet low-energy standards needs.
- *Conversion device*: Reducing consumption of thermal generators and fluid movers whose losses are due to wasted energy or equipment inefficiencies. Fuels are the most common source for heating while electricity is almost the unique source for cooling. Moreover, electric energy is used in transport subsystems and auxiliary equipment such as valve actuators. The use of solar thermal systems and an integrated building design approach can save energy by reducing heating requirements.
- *Energy resources*: Using daylight, natural ventilation, free cooling, passive cooling, heat pumps and on-site thermal or electric generation from renewable sources in order to reduce the need of external sources of energy.

As there is a chain, if a measure is employed it affects all the components of the whole chain. Thus, the main issues are described in-depth below.

11.4.1 Final Service

Global concern about reducing the use of energy and its impact on the environment has led to laws and standards to promote energy efficiency in different sectors. As HVAC systems represent an important part of the energy consumption in the building sector, such systems have a dedicated part in such energy regulations, as well as other matters concerning energy consumption such as lighting and the building envelope. The set of energy efficiency requirements for HVAC are diverse, both in qualitative and quantitative terms, due to the complexity of the energy management of a whole building in coordination with the different services (e.g. HVAC systems), and the great importance of climate and methods of construction. An in-depth review can be found of worldwide requirements set in the energy regulations for HVAC systems in buildings in [12].

11.4.2 Passive Methods

In this section a brief list and explanation of passive strategies and factors to be taken in consideration are described. The aim of these measures is to reduce the energy demand of the buildings and increase the user satisfaction in regard to their requirements of IEQ.

11.4.2.1 Local Climatic Conditions

In order to be able to exploit the local climate, it is essential that one analyses the climate type within which the site is located. The first task should be to collate the relevant climatic data (temperature, humidity, solar radiation, wind, etc.) that will inform the appropriate strategic design. The geographical location where the building is placed is the primary condition, but local conditions can differ significantly and will have implications for design.

11.4.2.2 Site Planning

The site location of the building can be influenced by some external factors related to the surroundings or the urban environment. These factors can slightly modify the local conditions, creating a microclimate. The microclimate is affected mainly by local topography, urbanization and vegetation. The use of vegetation as a bioclimatic measure has different effects: on the one hand, it improves the quality of air and conditions around the building in an urban environment that is beneficial to human health and comfort, on the other hand, from an energy perspective, the strategic placement of deciduous trees creates shade depending on the weather station and could also help to protect from the wind. Mainly important in the case of urban buildings, the features of the urban context could have a great influence regarding direct access to solar radiation, the shadows by surrounding buildings, the implications of the wind and air movement and the increase of air temperature referred to as the ‘heat island’ effect. In the case of urban sites, some aspects to be considered should be: the shape of the buildings (*L, H. I*, etc.), the height, the width of the streets and the existence of open spaces or backyards.

11.4.2.3 Orientation

The orientation of the building with respect to the sun’s path and wind direction is an aspect that will have a direct impact on the design of the building and of the envelope solution applied to the different orientations of the façades. The optimum situation in terms of solar orientation, for a linear building, is to be oriented west–east axis, where the west and east façades have minimal openings. Façades with good access to solar radiation can improve daylighting and reduce heating needs in winter due to the solar gains through the windows. Appropriate shading protection systems in hot climates or during the summer season will help to reduce cooling loads for south façades without losing the benefits of solar radiation at other periods of the year. In addition, the orientation of the building is important as it enables one to take advantage of the main directions of the wind and maximize the effects of natural ventilation by night if we want to cool the building in a hot period. On the other hand, orientation and façade design can help protect from cold winds in the winter.

11.4.2.4 Building Plan Section

Building plan section and form is influential in determining the potential interactions between the building and the environment. One of the key aspects is the shape of the building, which determines its compacity. The compacity relates the volume to the surface of the building that is external. A compact form minimizes heat losses to the exterior through the building envelope but makes it harder to profit from natural resources such as solar radiation or wind. The internal planning and distribution of spaces depending on the planned use (hall, offices, bedrooms, living rooms, service areas, etc.) will have implications for the energy and comfort performance. For example, in the case of a dwelling, internal planning that allows air circulation between opposing façades has great benefits with regard to the possibility of natural crossed ventilation. Buffer spaces, which are spaces that are used occasionally, can act as a thermal buffers. These semi-conditioned (tempered) buffer zones, such as atria, winter garden, accessible double façades, attic, etc. increase the building's energy performance.

11.4.2.5 Envelope

With regard to the external envelope of the building, there are several strategies that should be applied in order to reduce heating and cooling loads. Thermal insulation is a primary way of avoiding heat losses. Building regulations recommend maximum U-values for the walls and a maximum glass ratio (also known as WWR – Window to Wall Ratio) in order to minimize fabric heat losses. The U-value is a standard measure of the rate of heat loss conducted through a building component. In addition to the level of insulation or the percentage of windows, other important aspects for the opaque part of an external wall must be taken into account. Some of these aspects are the type of construction and the position of the insulation layer in a wall which affects the thermal mass of the building and its dynamic thermal performance. Vertical walls should be carefully treated, as well as roofs and floors, especially if they are in contact with unconditioned spaces or with the ground. Thermal bridges also increase the heat losses. Although it is impossible to build a house without thermal bridges, proper wall construction can reduce these to a minimum. The properties of the external surface of the wall with respect to its solar absorbance or reflectivity will affect the amount of solar radiation absorbed or rejected by the wall. Improving of the tightness of the building using, for example, better windows, helps to control undesired air infiltration from outside. Another key aspect is the properties of the windows or transparent elements in the façades. The WWR should be optimized with regard to the location of the building, its typology (residential, office, school, etc.) and the shading devices. They are two key figures that defines the thermal behaviour of a transparent element: one is the U-value and the other is the SHGC (Solar Heat Gain Coefficient) (also known as the g-value). The U-value in windows is larger than in the opaque elements. The U-value should be minimized to some extent if the reduction of heat loss is the driving strategy or if there is a high WWR. The SHGC is the ratio that measures the heat gain entering an indoor space through a window with respect to the incident solar radiation on the window's surface. When solar protection or better isolation properties are needed a variety of windows with different SHGC and U-values are available: sun protection, simple/double/triple glazing windows, glazing systems filled with gas, low-emissivity windows, etc.

11.4.2.6 Solar Protection

The installation of a high percentage of transparent elements in façades that are oriented to the south, which is beneficial during the winter months, can lead to a situation of significant solar gain, which could result of a decrease of thermal comfort in the summer. In order to control the radiation that is directly responsible for solar gains, shading devices should be considered. The shading element can be fixed or mobile and should be designed according to the orientation of

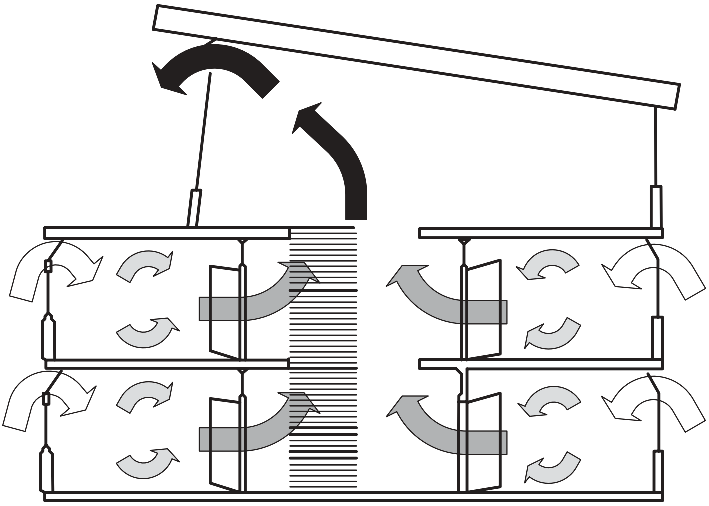

Figure 11.9 Example natural ventilation in summer at night

the opening and taking into account the direction of incidence of the solar radiation at different times of the year and during different times of day. The installation of solar protection should be properly sized so that the incident solar radiation is not compromised in the winter months.

11.4.2.7 Natural Ventilation

Ventilation is a way of providing the renewal rate required in terms of fresh air to ensure adequate indoor air quality. All the spaces of a building should be adequately ventilated in order to remove the pollutants that are generated during normal use of the spaces. Natural ventilation is a means of providing enough fresh air so it is an alternative to mechanical ventilation systems, which need electricity to operate. Additionally, natural ventilation can increase the thermal comfort of occupants, providing air movement to the indoor spaces and can be used to dissipate heat from a building without using air-conditioning. One of the strategies used in the summer or intermediate seasons is night ventilation. Night ventilation consists in leaving the air to circulate through the building by night (or even during the day) when the temperature of the outside air is below the required inside temperature. So the fresh air renews the heated air inside and also cools the mass elements that are part of the building (see Figure 11.9). Ground ventilation is a strategy that supplies air to the building from the outside through an air-hearth heat exchanger buried several metres in the ground. This technique allows one to pre-heat the air in winter or to cool it in summer due to the stable temperatures that occur two or three metres below the external ground surface.

11.4.3 Conversion Device

An HVAC system can improve its efficiency if efficient equipment is used at each of the four subsystems, specifically, air transportation, water transportation, cold generation and heat generation. The main elements of such subsystems are heat exchangers, fans and pumps. As these operate continuously while the system is working, they present a good opportunity for improving energy efficiency.

On the one hand, heat exchangers (coils, evaporators and condensers) are responsible of transferring heat or cold from the generators to the conditioned space. Although they do not use energy, their efficiency can be improved by increasing their transfer area.

On the other hand, fans and pumps are responsible for the movement of fluids (air, water, refrigerant) and are driven by electric motors. If such electric motors are fed through variable frequency converters (VFC), fans and pumps work more efficiently because they adapt their performance to the existing requirements avoiding inefficient on–off operation. Chapter 9 provides a more in-depth explanation of the advantages of such a solution. In contrast, as VFC are power electronics devices, they might drive harmonics during their operation, which might affect the general efficiency of the facility. This issue concerning power quality can be further understood by consulting [13].

Energy can also be saved by minimizing losses of thermal energy in transportation subsystems and preventing a simultaneous operation of heating and cooling subsystems. This can be achieved by a permanent automatic control of the variable parameters of the system. The use of an energy management control system (EMCS) in HVAC systems allows one to efficiently manage the energy in such systems as a whole. For example, an HVAC system in a large building covers different zones that are likely to have different thermal requirements. In order to provide an independent supply or extraction of the heat in each area an EMCS is fundamental.

At the core of an EMCS is a computer-based program where the data obtained from the sensors are processed for monitoring, controlling and optimizing the HVAC system, while achieving comfort and efficiency at the same time. The extra investment put into the devices and systems described earlier has a reduced payback due to the energy and operation savings obtained by its use.

The EMCS is not limited to HVAC applications and consists of a set of hardware devices and software connected via a communication network. The hardware includes:

- Sensors for obtaining the principal variable parameters of the system, that is, temperature, humidity, pressure, flow of air and water.
- Actuators that perform the action set by the control devices; such actuators normally are electric and pneumatic driven devices.
- Control devices that control the performance of actuators according to the data obtained from the sensors that are processed via the algorithms implemented in such devices. Such control is achieved by direct digital controllers, such as programmable logic controllers (PLC). Auxiliary devices such as relays might be required to interact with the actuators.
- Energy measuring devices allow one to obtain the energy consumption whilst the systems are working.

The software comprises a supervisory control and data acquisition (SCADA) system and data storage. The energy consumed by the whole HVAC system is monitored by the SCADA system. This allows one to supervise the operating conditions of the system and assess if the control strategies are performing well. Moreover, coordination with other systems of the building has to be considered, as for example with the fire-fighting system in order to stop air circulation in case of fire to facilitate fire extinction. A comprehensive description on the control of HVAC systems can be consulted in [14].

The communication link between hardware devices and software can be made according to different standard communication protocols (BACnet, LonWorks, Modbus, DeviceNet, Ethernet, TCP/IP, etc.), which can be either wireless or wired (which includes twisted pair cable, Power Line Carrier-PLC-, and fibre optic). Gateways are also usually needed in order to guarantee the interoperability, that is, the exchange of data between all the devices.

11.4.4 Energy Sources

The energy demand of an HVAC system is related to the building in which it works. A building is a very complex energy system where a large number of physical phenomena interact in a dynamic way. The building performance of a building is dependent on the site where it is placed, represented mainly but not only by the climatic conditions and the type of activity that might be carried on inside. Then, an Integrated Energy Design strategy is used for reducing the energy consumption.

The appropriate approach to designing buildings that provide high levels of comfort to its occupants and have the minimum impact in terms of the use of non-renewable resources is to use Integrated Energy Design. Many initiatives have been devoted to improving building codes [15,16], to developing guidelines for the industry [17], to improving design tools [18,19] and to increasing awareness in the final user who is seeking a building with low-energy consumption or even a zero energy building [17].

The Integrated Energy Design approach, by definition, is an inclusive approach that seeks the participation during the design process of all the design team members as well as the owner, project manager, maintenance representative, commissioning professional, etc. The other key point is to consider the building as a whole complex system where most of the aspects have a strong relationship. There are three key principles in Integrated Energy Design of low-energy buildings: 1) energy saving measures, 2) energy efficient systems and 3) renewable energy systems. The success of any energy building/project depends largely on how these three issues are addressed according to building type, use, location, climate environmental conditions (including availability for renewable resources), local energy infrastructure and financial resources, to name a few. Figure 11.10 illustrates the three key principles of Integrated Energy Design (IED): Passive Approaches (PA), Energy Efficient Systems (EES) and Renewable

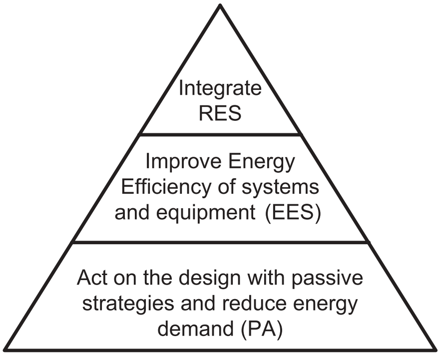

Figure 11.10 Principles of the Integrated Energy Design

Energy Systems (RES). The first principle in the IED process focuses on reducing the amount of energy needed through passive approaches. Given the inherent needs of artificial lighting and possible heating and/or cooling, the second principle aims at implementing energy-efficient systems. The renewable energy systems are needed to offset in large measure the energy demand required for lighting, heating and cooling (the third principle).

The HVAC designer will be aware of any passive heating and cooling strategies that can be promoted during the early stage of the design. By the same token, every kilowatt obtained from renewable energy to provide pre-heating and/or pre-cooling will have a major impact on HVAC equipment sizing. Through integrated design, the HVAC engineer will have the capacity to influence some key features of the building envelope such that passive strategies will be put forward. The cost benefit of renewable energy will also be taken into account by the HVAC engineer during the course of the design. The integration of renewable energy is often seen as an optional design feature, but when included in a whole building simulation analysis it has the potential to offset a significant portion of the heating and cooling loads. Therefore, the HVAC design of a low or nearly zero energy building will be part of an integrated design approach with an emphasis on the role of passive strategies and the integration of renewable as a way to reduce the peak loads and consequently the size of the HVAC equipment.

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