Chapter 2
Energy-Efficient Building Design

Abstract The current chapter discusses a number of important aspects whose influence on the energy efficiency of new buildings calls for their careful consideration as early as in the design phase. With the basics of energy-efficient building design figuring in Sect. 2.1, the next important topic contained in Sect. 2.2 deals with commonly used classification systems determining the energy efficiency level of buildings. In order to understand energy-efficient design principles, basic facts on energy flows in buildings are given in Sect. 2.3. The relation between the building design, climatic influences and the building site analysis can be found in Sect. 2.4. Section 2.5 introduces a set of main design parameters, such as orientation, shape of the building, zoning of interior spaces and the building components. Description of the building components focuses mainly on those composing the building thermal envelope, with glazing surfaces and timber construction being only briefly presented, while a more detailed specification of the two materials follows in Chaps. 3 and 4. For the complexity of energy-efficient design, passive design strategies comprising passive solar heating, cooling, ventilation and daylighting are considered in Sect. 2.6. Finally, Sect. 2.7 provides an overview of the role of active technical systems, since they have become an indispensable constituent element of contemporary energy-efficient houses.

2.1 Basics of Energy-Efficient Building Design

Climate-conscious architecture, bioclimatic architecture or energy-efficient architecture are commonly used terms presenting specific approaches in contemporary architectural building design, which have to be applied in conjunction with the structural, technical and aesthetic aspects of architecture. Nevertheless, general guidelines related to building design along with its relation to the environment are not a novelty since they are to some extent based on vernacular architectural principles having existed for centuries. On the other hand, the reflection of the current global energy situation is seen in the demand for energy-efficient building

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design to be determined by precisely defined parameters which affect the energy balance of buildings (Fig. 2.1).

Energy-efficient building design requires a careful balance of the energy consumption, energy gain and energy storage. As shown in Fig. 2.1, the basic design principle integrates the building components into a system taking maximum advantage of the building's environment, climatic conditions and available renewable energy sources. The aim is to reduce the need for conventional heating and ventilation systems, which are inefficient and consume fossil energy sources. The use of contemporary active technical systems exploiting renewable energy is therefore advised instead. Apart from higher energy efficiency and reduced environmental burdening, energy-efficient building design results in a comfortable indoor climate, which is of utmost importance for the occupants' well-being. The occupants play an important role in the system of energy-efficient buildings, since only with proper use can the buildings' energy balance reach a level planned by the engineers.

Planning and designing energy-efficient buildings is a complex process whose definition could be understood as a three-levelled one. The first basic design level comprises an optimum selection of the building components, i.e., the structural design concept, thermal envelope composition, construction details, type of glazing and other materials, with respect to the location, climatic data and a suitable orientation. The following level is that of passive design strategies which allow for heating with solar gains, cooling with natural ventilation, using thermal mass for energy storage where renewable energy sources are exploited with no need for electricity. Only the third, i.e., the last level involves design concepts of the building's active technical systems using renewable sources of energy with the necessary recourse to electrical energy. Efficient planning and design of buildings aims at skilfulness and originality of design concepts at the first two levels to the extent where the need for active systems arises within the least possible degree.

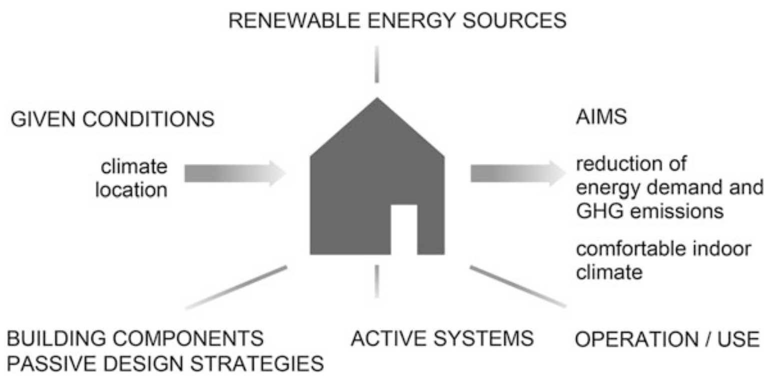


Fig. 2.1 Basic principle of energy-efficient design

2.2 Classification of Buildings According to Energy Efficiency

Energy efficiency requirements in building codes can ensure that concern for energy efficiency is taken in the design phase, which leads to realization of large potentials for achieving good energy efficiency standards in new buildings [19]. Currently, there exists no common classification of energy-efficient buildings. On the contrary, there is a variety of standards and energy labels used in the construction industry across Europe with commonly appearing terms, such as low-energy house, passive house, zero carbon house, zero energy house, 3-litre house etc., [9].

To determine specific energy standards for buildings, many European countries use classification systems based on national building codes or recur to launching special labels, e.g., the Swiss Minergie, German Passive House or Austrian Klima:aktiv House. In order to achieve a certain label or be classified into a specific standard determined by the building codes, a building has to satisfy specific-energy consumption-related requirements which are not uniform to all classification systems. The existing classification systems vary mainly in the type of energy taken into account. Certain systems focus merely on the specific energy demand for space heating while others also consider CO_2 emissions or even respect additional types of energy use, for instance primary energy demand. Only rarely will classification systems take into consideration a complex set of energy indicators integrating all types of the energy use in buildings, where apart from the ones mentioned above, the energy use for space cooling, water heating, air conditioning, consumption of electricity, etc., proves to be of vital importance. Furthermore, some classification systems introduce separate measures for residential and public buildings, for small and multi-storey buildings, for new and renovated buildings. A number of countries established requirements modified for different regions. Generally, a certain energy standard is achieved through structural measures and active technical systems. User behaviour has no effect on the standard, although it does affect the actual energy consumption.

To illustrate the requirements for different standards, a few of the existing classification systems are presented in Tables 2.1, 2.2 and 2.3.

The data in Table 2.1 show variations of two national systems used to determine the building's energy label. The goal referring to the maximum energy demand for heating in new buildings set in the Slovene National Building Regulations is around 50–60 kWh/m^{2}a with that of the Austrian National Building Regulations being below 50 kWh/m^{2}a. A building satisfying the above goals can be treated as energy-efficient; however, the aim is to design buildings in a manner to use less energy than defined by the maximum value set in the building codes. Instead of classes A, B and C, a descriptive terminology based on labels is more widely used in the construction industry. The rates of energy consumption in buildings commonly used in Austria are presented in Table 2.2.

Table 2.1 Slovene classification of the building's energy efficiency (Rules on the methodology of construction and issuance of building energy certificates 2010) and Austrian classification of the building's energy efficiency [20, 23]

Energy class	Annual heating demand Q_h [kWh/m^{2}a]	Energy class	Annual heating demand Q_h [kWh/m^{2}a]
A1	0–10	A++	≤10
A2	10–15	A+	10–15
B1	15–25	A	15–25
B2	25–35	B	25–50
C	35–60	C	50–100
D	60–105	D	100–150
E	105–150	E	150–200
F	150–210	F	200–250
G	210–300	G	250–300

Table 2.2 Austrian classification of the building's energy efficiency on the basis of commonly used labels for construction industry

Label	Annual heating demand Q_h [kWh/m^{2}a]	
	Small buildings <130 m^2	Multi-storey buildings
Passive house	≤10	≤10
Super low-energy house	10–36	10–20
Low-energy house	36–45	20–25

The above classification has separate requirements for multi-storey buildings and smaller buildings whose floor area is lower than 130 m^2.

The German classification system, based on the requirements defined by Energieeinsparverordnung für Gebäude 2009, EnEV [8], is completely different. Buildings are rated according to the level of improvement of energy performance determined in EnEV [8]. It should be noted that the amended Energieeinsparverordnung für Gebäude the EnEV 2014 is currently under adoption. On the other hand, the Passive House Institute registered their own label for buildings with special design requirements called the "Passive House Certificate" [10]. Table 2.3 shows a selection of energy standards currently applied in Germany.

In general, the existing classification systems are based on the directives which are modified within a specified time period. Some of the systems presented in Tables 2.1, 2.2 and 2.3 arise from the building codes based on the European directive on energy performance of buildings which requires classification of all new buildings according to the energy certificate whose validity lasts for 10 years.

The current section deals mainly with factors which produce influence on the energy efficiency of buildings and can be taken into consideration in the design stage. The level of energy efficiency can be calculated by using the existing software tools. In order to understand energy-efficient design principles presented later in this chapter, some basic knowledge on energy flows in buildings is required.

Table 2.3 German classification of the building's energy efficiency

Energy class	Annual heating demand Q_H [kWh/m^{2}a]	Primary energy demand Q_P [kWh/m^{2}a]	Final energy demand Q_e [kWh/m^{2}a]	Heat transmission losses H'_T
Plus energy house		≤0	≤0	
Passive house	≤15	≤120**		
*KfW—energy-efficient house 40 [8]		≤40 % of the ***maximum value set in EnEV 2009		≤55 % of the maximum value set in EnEV 2009
KfW—energy-efficient house 55 [8]	≤35	≤55 % of the maximum value set in EnEV 2009		≤70 % of the maximum value set in EnEV 2009
KfW—energy-efficient house 70 [8]	≤45	≤70 % of the maximum value set in EnEV 2009		≤85 % of the maximum value set in EnEV 2009
KfW—energy-efficient house 85 [8]	≤55	≤85 % of the maximum value set in EnEV 2009		≤100 % of the maximum value set in EnEV 2009

German classification of the building's energy efficiency on the basis of the Energieeinsparverordnung für Gebäude 2009, EnEV [8], Förderstufen der KfW Bankengruppe and Passive house [10], definitions

* KfW—Funding levels of the KfW Bank Group

** Maximum value for Q_p set in Feist [10] contains the requirements for heating, water heating, cooling, ventilation and household electricity

*** Maximum value for Q_p set in EnEV is approximately 60 kWh/m^2 a and contains no demand for household electricity

2.3 Energy Flows in Buildings

A building can be considered as a thermal system with a series of heat flows, inputs and outputs [24], such as the transmission heat losses or gains (Q_t), ventilation heat losses or gains (Q_v), internal heat gains (Q_i) and solar heat gains (Q_s). The thermal response of the building is preconditioned by the relationship between the heat gains and losses, where the sum of all energy flows results in the amount of energy (ΔQ) that has to be supplied to or extracted from the building in order to reach a comfortable indoor living climate. If the sum of all heat flows is zero, the building is reaching the thermal balance.

The following equation shows the main heat flows in a building exerting influence on the indoor living climate:

$$Q_t + Q_v + Q_i + Q_s = \Delta Q \tag{2.1}$$

where the main quantities are the following:

Q_t transmission heat losses or gains caused by heat flow through the elements of the building envelope,

Q_v ventilation heat losses or gains caused by air exchange between the building and its surrounding (air infiltration, natural ventilation, mechanical ventilation, air leakage through the building envelope),

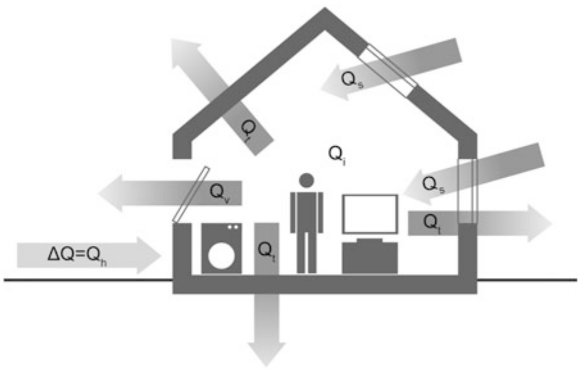
Q_i internal heat gains generated inside the building by occupants, lighting and household appliances,

Q_s solar heat gains caused by solar radiation

Based on the different temperatures of the building and its surroundings, we can distinguish between two opposite heat flow scenarios. In cold periods of the year when the average outdoor temperature is generally lower than the indoor temperature, the sum of all heat flows in a building is usually negative, mainly due to the energy output caused by transmission and ventilation heat losses (Fig. 2.2). In such cases, the ΔQ results in the amount of energy required for heating (Q_h—energy demand for heating) in order to reach a desired indoor temperature of approximately 20 °C, typical of cold periods.

The opposite is the warm period scenario, i.e., that of the summer period in the majority of European areas, when the highest daily outdoor temperature can be higher than the indoor temperature. The sum of all heat flows in a building results in a positive value, mainly due to solar heat gains. The ΔQ shows the amount of heat that has to be extracted from the building, (Q_c—energy demand for cooling), in order to reach a desired indoor temperature which should not exceed 25 °C. Energy flows described in this subsection refer to natural flows and do not take heat exchange caused by active technical systems into account.

Fig. 2.2 Energy flows in a building typical of cold periods



2.4 Climatic Influences and the Building Site

The importance of climate as a major determinant of the style of houses was pointed at as early as in Vitruvius [25]. Thorough inspection of the location has always been a first step in the process of planning and designing buildings. Numerous examples of vernacular architecture show how the building design responds to climatic conditions. Considerable differences in architecture typical of individual regions came to existence as a consequence of the response to specific location features comprising climatic characteristics of a larger region on the one hand and those of a particular location and its surrounding area on the other. From the point of view of bioclimatic planning, which is a basis for achieving the energy efficiency of buildings, location analysis is vitally important since numerous building designing aspects depend on the location specifics. It is thus possible to define the topography of the terrain, its soil composition and vegetation, the position and shape of the neighbouring buildings, the openness of the site, its orientation and most significantly, climatic circumstances. The latter have a major role in planning the building's heating, cooling and natural lighting strategies.

2.4.1 Global Climatic Impacts

Design principles considering the impact of the sun encompass two essential aspects: the apparent movement of the sun and solar radiation energy [24].

The earth moves around the sun in an elliptical orbit. At the same time, it spins in a counter-clockwise direction around its own axis once a day. The earth's axis is not normal to the plane of the earth's orbit, but tilted by 23.5°. Due to the tilt of the earth, not every place on earth gets an equal amount of sunlight every day, i.e., certain places have extremely short duration of daily light. As the earth revolves around the sun during a year, the angle between the earth's equatorial plane and the earth–sun line varies from +23.45° around 22 June to 0° around 21 March and 22 September, and to −23.45° around 22 December. This motion causes the phenomenon of seasons. For instance, when the northern pole is tilted towards the sun, the northern hemisphere experiences summer, while the places in the southern hemisphere get winter.

The plane of the earth's orbit is called the ecliptic and presents a reference plane for the positions of most solar system bodies. Since the earth orbits the sun, the sun is also on the ecliptic. Viewed from the earth, the sun appears to us as moving around the sky on the ecliptic. The apparent position of the sun can be determined by two angles, altitude and azimuth (Fig. 2.3).

The altitude (ALT) or solar elevation angle is the angle between the direction of the geometric centre of the sun's apparent disc and the idealized horizon, while the azimuth (AZI) is defined as the angle from due north in a clockwise direction. The angle indicating north is 0°, 90° for the east, 180° for the south and 270° for the west.

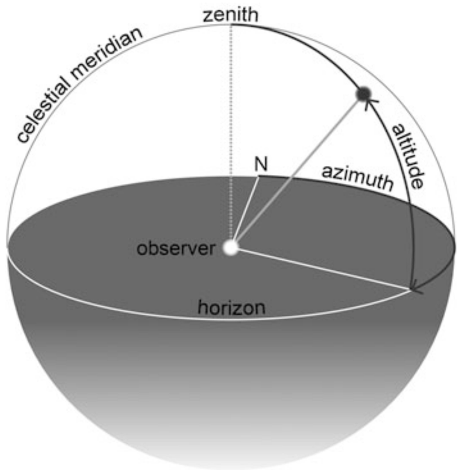


Fig. 2.3 Azimuth and altitude angles for northern latitudes

The apparent motion of the sun shows the sun as rising approximately in the east, moving through the south in a clockwise direction and setting approximately in the west. The sun rises due east and sets due west only on the first day of spring, 21 March and on the first day of autumn, 22 September. The apparent position of the sun varies for different hours of a day, days of the year and for different destinations.

For the purposes of energy-efficient building design, it is important to be aware of the sun's apparent movement when analysing the specified location of the building. Owing to the above-mentioned awareness combined with solar radiation and other climatic data, it is possible to make predictions for certain periods of the year and certain destinations in the sense of knowing where to lay focus in the process of designing, on passive solar heating or on prevention of overheating. Table 2.4 presents the position of the sun on two important dates, 21 June and 21 December.

The above data derived through free access to the sun-position-calculator software show divergence of the inclination angles of sunrays (ALT) at the summer solstice, from 54° in Tallinn, Estonia to 75.5° in Athens, Greece. In Tallinn, the sun rises at an azimuth angle of 36° east and sets at 324° west with the apparent sun path of 288°, which indicates very long summer days. On 21 December (winter solstice), the ALT at solar noon varies from 7.2° in Tallinn to 28.6° in Athens. The length of the day in Tallinn is very short, with the sunrise at an azimuth angle of 139° and the sunset at 221°, which shows that only southern façades can be directly exposed to the sun in winter. In Athens, the sun rises at an azimuth angle of 120° and sets at 240° (Fig. 2.4), with the apparent sun path of 120°, which indicates the longest winter day if compared to other cities from the Table 2.4.

Data for the main sun position over the course of a year have a crucial role in estimating elements such as the orientations of the building that will be exposed to

Table 2.4 Sun position at the summer and winter solstice for different destinations in Europe

Location	Latitude	Longitude	ALT solar noon on 21–06	AZI sunrise sunset on 21–06	ALT solar noon on 21–12	AZI sunrise sunset on 21–12
Tallinn	59.43°N	24.75°E	54°	36° 324°	7.2°	139° 221°
Copenhagen	55.68°N	12.56°E	57.8°	43° 317°	11°	133° 227°
London	51.50°N	0.12°E	61.9°	49° 311°	15.1°	128° 232°
Ljubljana	46.05°N	15.52°E	67.4°	54° 306°	20.6°	124° 236°
Madrid	40.42°N	3.70°E	73°	58° 302°	26.2°	121° 239°
Athens	37.98°N	23.73°E	75.5°	60° 300°	28.6°	120° 240°

Source http://www.timeanddate.com/ [27]

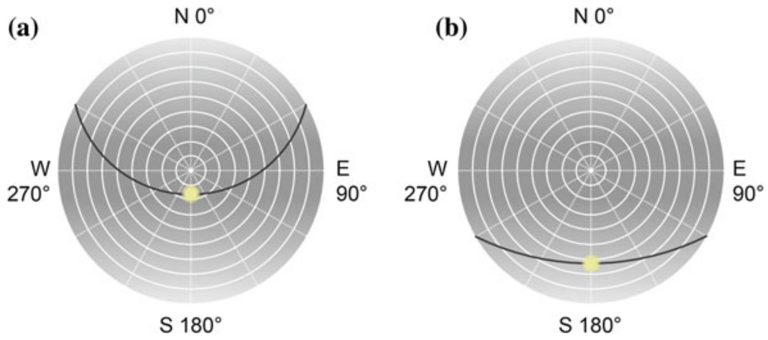


Fig. 2.4 Two-dimensional projection of the apparent sun path on: **a** 21 June and **b** 21 December, for Athens, Greece

direct radiation, the orientations of the glazing that will contribute to solar gains and the extent of the latter, the depth of the sunrays penetration into a room, the shape and size of the shading elements to be selected, etc.

For the effective implementation of passive solar design strategies, it is necessary to be aware of the basic facts about solar radiation. Approximately 70–75 % of the solar electromagnetic radiation enters the earth's atmosphere and reaches the earth. The electromagnetic solar radiation reaching the earth consists of three wavelength intervals (Fig. 2.5):

- Ultraviolet radiation (UV), 280–380 nm, which is harmful since it produces photochemical effects, bleaching, sunburn, etc.
- Visible light (VIS), 380–780 nm, ranging in colour from violet to red.
- Near infrared (NIR), 780–2,500 nm, also known as thermal radiation.

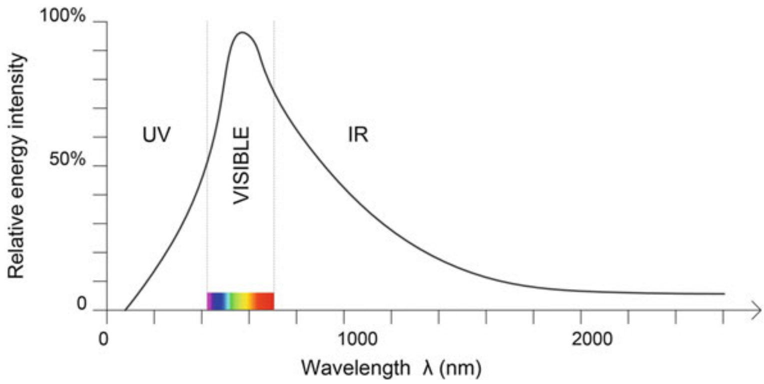


Fig. 2.5 Division of solar radiation according to the wave length

The incoming radiation is partly reflected back into space and partly absorbed by the atmosphere, clouds and the earth's surface. The absorbed radiation causes warming up of the earth's surface, and when the surface is warmer than the environment, it emits long-wave far-infrared radiation (FIR) with wave lengths of 2,500–50,000 nm. The emitted FIR is partly (15–30 %) transmitted back to the space and partly (70–85 %) reflected back to the earth. This leads to a further temperature increase on the earth.

Solar radiation can be measured as "irradiance" denoting the intensity [W/m^2] or as "irradiation" denoting an energy quantity over a specified period of time [Wh/m^2], [24]. There are large variations in irradiation at different locations on the earth due to different reasons, e.g., the angle of incidence, atmospheric depletion and the length of daylight period from sunrise to sunset. The annual total horizontal irradiation, also called global horizontal irradiance (GHI), for different destinations on the earth varies from approximately 400 kWh/m^2 near the poles to approximately 2,500 kWh/m^2 in the Sahara desert [24]. The global horizontal irradiance is the sum of the incident diffuse radiation and the direct normal irradiance (DNI) projected onto the horizontal surface, where the diffuse radiation is a combination of the radiation reflected from the surroundings and atmospherically scattered radiation.

Awareness of the solar radiation potential for a selected building site is vitally important for the purpose of achieving the energy efficiency. For instance, while planning to build a house in an area with low solar radiation and low average yearly temperatures, the main focus needs to be laid on excellent insulation. On the other hand, in the case of high solar radiation, the house should have larger south-oriented glazing areas, since winter solar radiation can be extremely beneficial for the building's energy balance. Data on solar radiation are treated as one of the main climatic indicators. In general, climatic conditions are one of the initial decision factors in designing an energy-efficient building.

2.4.2 Macro-, Meso- and Microclimate

Climatic conditions may be considered at three levels: macroclimate, mesoclimate and microclimate.

Macroclimate is a general climate of a region which encompasses large areas with fairly uniform climatic conditions. These vary from region to region due to the following factors: latitude (distance from the equator), altitude (height above sea level), topography (surface features), distance from large water bodies (oceans, lakes) and circulation of winds. Macroclimate is described by major climatic indicators provided by meteorological stations, such as temperature, humidity, air movement, i.e., wind (velocity and direction), precipitation, air pressure, solar radiation, sunshine duration and cloud cover.

Local characteristics of the area such as topography (valleys, mountains), large geometric obstructions, large-scale vegetation, ground cover, water bodies as well as occurrence of seasonal winds cause modification of general macroclimate conditions. These modified conditions denote the climate of a smaller area, also called mesoclimate. In [12], general types of mesoclimate having similar features are coastal regions, flat open country, woodlands, valleys, cities and mountainous regions.

The third level or the microclimate level is defined by taking into account human effect on the environment and consequently the way it modifies conditions within a specific area in the size of the building site. For instance, planted vegetation and nearby buildings influence the site's exposure to the sun and wind. Water and vegetation affect humidity whereas the built environment modifies air movement and air temperature [12].

Climatic classification systems define several climatic regions at the level of macroclimate. There is a variety of the existing climatic classification systems used for different purposes. One of the most recognized is the Köppen–Geiger system based on the concept of native vegetation. The original system underwent a number of modifications, which led to the current use of such modified systems [18, 22], distinguishing between five basic climate types; A-tropical, B-arid, C-temperate, D-cold and E-polar subdivided into subtypes according to temperature and precipitation data. Table 2.5 describes Köppen climate symbols.

Since the current book deals predominately with the building design suitable for European regions, Fig. 2.6 offers a more detailed description of European climate.

Europe is bounded by areas of strongly contrasting physical features that influence regional climate conditions. These areas are represented by the Atlantic Ocean to the west, the Arctic Sea to the north, a large continental part to the east and the Mediterranean Sea and north Africa to the south [12]. Northern zones influenced by north winds are known for cold winters with low solar radiation and mild summers. Mid-European areas close to the Atlantic Ocean influenced by humid western winds are known for cool winters and mild summers with a relatively high level of humidity reducing the strength of solar radiation. Central Europe has cold winters and warm summers, while southern Europe experiences

Table 2.5 Description of Köppen climate symbols and defining criteria [18, 22]

1st	2nd	3rd	Description	Criteria[1]
A			Tropical	$T_{cold} \geq 18$
	f		Rainforest	$P_{dry} \geq 60$
	m		Monsoon	Not (Af) and P_{dry}_100–MAP/25
	w		Savannah	Not (Af) and P_{dry} <100–MAP/25
B			Arid	MAP <10°—$P_{threshold}$
	W		Desert	MAP <5°—$P_{threshold}$
	S		Steppe	MAP_5°—$P_{threshold}$
		h	Hot	MAT_18
		k	Cold	MAT <18
C			Temperate	T_{hot} >10 & 0 < T_{cold} <18
	s		Dry summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	f		Dry sinter	$P_{wdry} < P_{swet}/10$
	w		Without dry season	Not (Cs) or (Cw)
		a	Hot summer	T_{hot}_22
		b	Warm summer	Not (a) & T_{mon}10_4
		c	Cold summer	Not (a or b) & 1_T_{mon}10 < 4
D			Cold	$T_{hot} > 10$ & T_{cold}_0
	s		Dry summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		Dry winter	$P_{wdry} < P_{swet}/10$ f—Without dry season Not (Ds) or (Dw)
	f		Without dry season	Not (Ds) or (Dw)
		a	Hot summer	T_{hot}_22
		b	Warm summer	Not (a) & T_{mon}10_4
		c	Cold summer	Not (a, b or d)
		d	Very cold winter	Not (a or b) & $T_{cold} < -38$
E			POLAR	$T_{hot} < 10$
	T		Tundra	$T_{hot} > 0$
	F		Frost	T_{hot}_0

[1] *MAP* mean annual precipitation, *MAT* mean annual temperature, T_{hot} temperature of the hottest month, T_{cold} temperature of the coldest month, T_{mon} number of months where the temperature is above 10, P_{dry} precipitation of the driest month, P_{sdry} precipitation of the driest month in summer, P_{wdry} precipitation of the driest month in winter, P_{swet} precipitation of the wettest month in summer, P_{wwet} precipitation of the wettest month in winter, $P_{threshold}$ varies according to the following rules (if 70 % of MAP occurs in winter, then $P_{threshold}$ 2 × MAT; if 70 % of MAP occurs in summer, then $P_{threshold}$ 2 × MAT + 28, otherwise $P_{threshold}$ 2 × MAT + 14). Summer (winter) is defined as the warmer (cooler) six-month period of ONDJFM and AMJJAS

hot summers and mild winters with high solar radiation. A more accurate division of climate types according to the updated Köppen–Geiger climate classification is shown in Fig. 2.6. At the macrolevel, Europe is characterized by four climate types, where the dominant type according to the land area size is cold (D), followed by arid (B), temperate (C) and polar (E) climate types, with the latter being found within a smaller surface range [22]. All of the mentioned types are divided into subtypes of the second and third ranges (Table 2.5 and Fig. 2.6), which exhibit different features related to temperature and precipitation. Studies on the

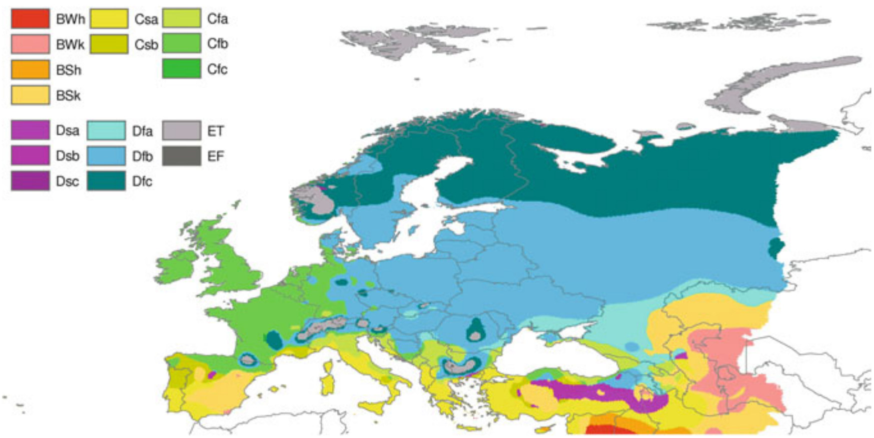


Fig. 2.6 European part of the updated world map of the Köppen–Geiger climate classification [22]

optimal glazing size and building shape presented in Sect. 4.3 are based on temperate and cold climates, Cfb and Dfb.

Apart from temperature and precipitation data, which are basic classification factors of the presented Köppen–Geiger system, the amount of solar radiation in combination with air movement characteristics composes another essential data base for the purposes of energy-efficient building design.

Solar radiation data can be obtained from maps of irradiation or through special software packages. The database is usually compiled from measurements of global horizontal solar irradiation and other meteorological and climatological parameters within a specific reference period.

Air movement affects thermal comfort of a building through convection and infiltration. Air movement or wind speed and its direction are usually measured at a height of 10 m. Wind data can be best presented by graphs with wind-rose diagrams showing the frequency of winds blowing from particular directions over a specific reference period.

When analysing a certain building site, it is necessary to consider climatic data at macro-, meso- and microclimate levels. As mentioned previously, the main climatic indicators can be modified to a certain extent by local topography, vegetation, surrounding buildings, etc. For instance, daily air temperature in wooden areas can be lower by a few degrees than that of open areas, since tree foliage reduces the amount of solar radiation hitting the ground. In the nighttime, tree foliage impedes the outgoing long-wave radiation and a drop in the air temperature is therefore lower [12]. The air temperature can also be influenced by topography, ground surface, the surrounding buildings and the vicinity of water areas. Likewise, solar radiation can be weakened by dust particles in the air or largely hindered by some geometric obstructions like hills, buildings or, as explained beforehand, by vegetation.

While the general macro- and mesoclimates of the region are beyond human influence, some significant benefits can be provided by human effect on the environment at the microclimatic level [12]. All in all, a good understanding of the regional and local climate means an essential input into a most effective building design process.

2.5 Basic Design Parameters

As mentioned beforehand, a complex design approach to energy-efficient buildings may be conducted at three levels. The primary or basic design level includes determination of the building shape and orientation in addition to the arrangement of interior spaces and selection of the building components. Energy balance of the building is enhanced through design of passive strategies, while the final design phase step goes to application of active technical systems.

2.5.1 Building Shape

The building shape is defined by geometry of external building elements, such as the walls, floor slab and roof. It has a significant effect on thermal performance, since major heat flows (cf. Sect. 2.3) pass through the building envelope.

The building shape can be expressed by the shape factor (F_s) defined by the equation:

$$F_S = \frac{A}{V} \ \left[\mathrm{m}^{-1}\right] \tag{2.2}$$

where the equation quantities are the following:

A total area of the building thermal envelope [m^2]
V total heated volume of the building [m^3]

To minimize transmission losses through the building envelope, a compact shape indicated by a low shape factor is desirable (Fig. 2.7). On the other hand, a dynamic form with larger transparent surfaces enables provision of higher solar gains. Integrating the aspect of solar access into the phase of determining the building shape is an essential part of energy-efficient building design [13]. According to general design guidelines for energy-efficient houses, a compact rectangular shape is seen as the optimum. However, some studies show that under certain location and climatic conditions, a dynamic shape might be even more efficient as far as energy gains are concerned. Further interesting findings relating to the building shape are presented in Sect. 4.2.2.

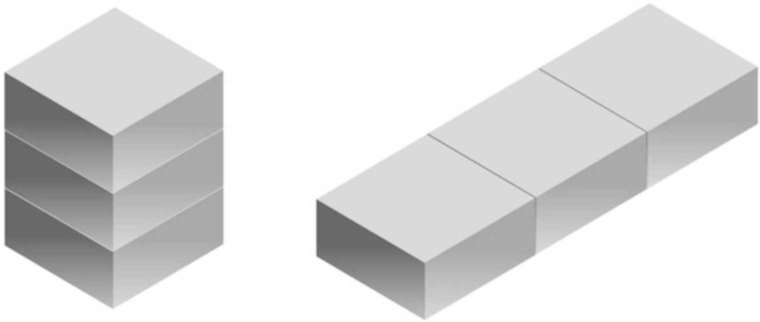


Fig. 2.7 Shape factor is defined by the ratio between the area of the building thermal envelope and the heated volume

Another parameter referring to the proportions of the building is called the building aspect ratio (*AR*). It is defined as the relationship between linear dimensions of individual external building elements. It can denote the relationship between the building's height and width ($AR_H = H/W$) or between the building's length and width ($AR_L = L/W$). When considering solar access to selected building elevations, the relationship between the equator-facing façade length and the lateral façade length can play an important role. Design guidelines usually require that buildings be oriented with a longer glazed façade to the south to ensure higher solar gains. Figure 2.8 presents a relationship between the length and the width of the building.

When buildings feature more dynamic and fractured forms, the issue of solar access to individual parts of the envelope proves to be of great significance since some parts of the building could shade the others. Many studies therefore treat the geometric relationship between the shaded and exposed part of the building envelope and its influence on solar gains. Figure 2.9 presents a relationship between the exposed and partly shaded façade.

Defining the building shape should respond to the building's environment and particularly to climatic conditions. Observation of vernacular buildings in different climatic regions shows a number of differences. Massive walls, small windows and flat roofs are typical of buildings in hot and dry climates with significant diurnal temperature differentials. Massive walls ensure adequate thermal mass for thermal inertia (cf. Sect. 2.6.1), small windows prevent overheating during summer days and flat roofs prove to be a suitable choice, since there is usually little precipitation. Even the principles of spatial planning take high solar radiation into account, which leads to buildings often being closely clustered for the purposes of shading one another and the public spaces between them. On the other hand, vernacular building design is quite different in hot and humid climates. The use of large windows exposed to cooling breezes enables summer cooling while large

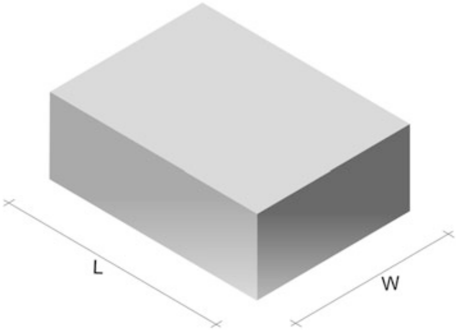


Fig. 2.8 Aspect ratio L/W—relationship between the length and the width of the building

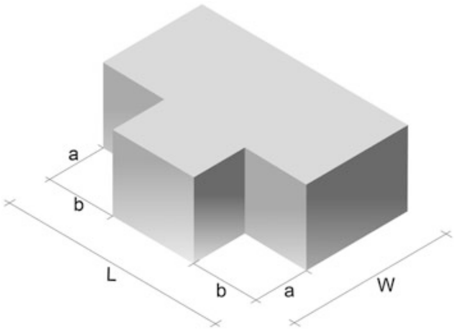


Fig. 2.9 Geometric relationship between the exposed and partly shaded façade

overhangs and shutters provide protection from solar radiation and rainfalls [7]. Massive structure is not typical since there are small differences between day—and nighttime temperatures. Finally, buildings in a predominantly cold climate need a compact form with a minimal shape factor reducing heat losses through the envelope.

2.5.2 Orientation

Building orientation is defined as the angle between the normal to a certain surface, e.g., façade, and the north cardinal direction. It is determined for each of the building's façades. North orientation is thus defined by the angle of 0°, south by the angle of 180°, east by the angle of 90° and west by the angle of 270°. An additional explanation regarding the terms "south, north, east and west" is necessary at this point. "Facing the equator" or "equatorial orientation" are terms frequently used to describe the orientation with respect to the northern and southern hemispheres. For the northern hemisphere, equatorial orientation denotes south orientation. Since the current book and especially the studies presented in

Sect. 4.3 deal mainly with buildings located in the northern hemisphere, the term “south” orientation will be used as a synonym for equatorial orientation.

With respect to guidelines for energy-efficient housing, a major part of the building’s transparent surfaces should be oriented to the south. South orientation enables higher solar gains and better daylighting, but at the same time, it increases a risk of summer overheating. In order to prevent overheating, a well-designed solar control is indispensable for the buildings located in a great number of European regions. A study treating the issue of the optimal size and distribution of the glazing surfaces can be found in Sect. 4.3.1.

Certain building sites may be less favourable in terms of orientation, since they cannot enable the orientation of the building mainly to the south. The task of architects in such cases is to take maximum advantage of the existing conditions by adjusting the design concept to suit the given microlocation.

An exemplary case of such design pursuit is the Sunlighthouse in Pressbaum, Austria, developed by the architects of Hein-Troy Architekten for the Model Home 2020, a project set by the Velux Group. The specifics of the terrain and the vicinity of the neighbouring buildings in addition to the mainly south-east-oriented site were a challenge for the architects who conceived well thought out strategies, such as positioning of the atrium, using different roof slants, allowing for natural lighting to penetrate through the roof windows, in order to prove that a house can have an excellent energy certificate and a comfortable indoor climate in spite of the rather undesirable microlocation conditions (Fig. 2.10).

2.5.3 Zoning of Interior Spaces

Zoning is a term used for division of a building into spaces having similar characteristics based either on the purpose of individual spaces or on interior climate conditions. Energy-efficient building design requires careful consideration of indoor zoning in order to create a rational distribution of heat and daylight. There are several zoning concepts which strongly depend on the type, size and the purpose of a building.

Appropriate thermal zoning can result in lower heat flow between individual spaces in the building or between the building and its surroundings. One of the frequently used thermal zoning concepts suggests positioning rooms with a low interior temperature (e.g., staircase, pantry and entrance hall) next to the north-facing exterior wall which tends to be cooler than the south-facing wall, due to less intense exposure to solar radiation. On the contrary, spaces such as the living room, dining room or bedrooms for children which demand a slightly higher air temperature belong to the south-facing side where additional heating is provided through solar radiation (Fig. 2.11). Another important part of building design is vertical thermal hierarchy; a basement placed inside the thermal building envelope needs to have good insulation and constant heating while a non-heated basement should be placed outside the thermal envelope. In the latter case, the entire ground

Fig. 2.10 Sunlighthouse in Pressbaum, Austria (Photo by Samo Lorber)

floor above the basement is required to have suitable insulation. The staircase, a special zone and a connecting element between a cold basement and the heated living area, thus becomes a critical point of thermal bridging. In order to prevent heat losses, a buffer zone with insulating doors must be planned, which leads to a thermal bridge being avoided.

Thermal zoning in public buildings tends to be more complex since a basic linear alignment of spaces to the north, middle and south zones does not always prove to be suitable. Nevertheless, it is sensible to group rooms with similar characteristics even in large-size buildings for the purposes of functionality and heating requirements.

A further essential element to be foreseen is daylight zoning. Rooms functioning as places for work, play or residence require substantial lighting and are thus positioned alongside the glazed façades while a more central placement suits rooms demanding less daylighting. The result of such zoning is excellent indoor climate and lower electricity consumption.

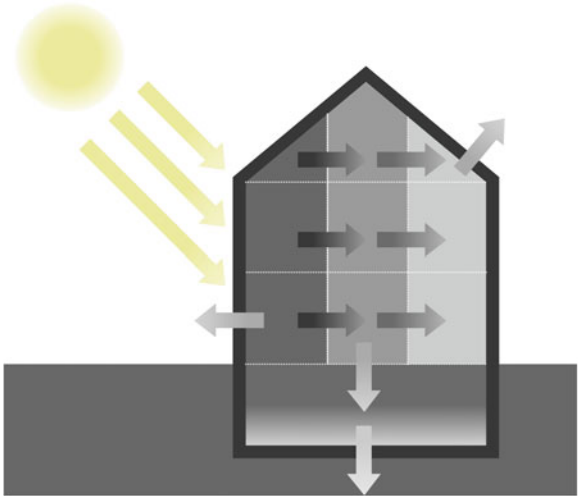


Fig. 2.11 Thermal zoning of interior rooms in a single-family house

2.5.4 Building Components

In general, a building consists of structural elements, elements of protection and finalization and active technical systems. Structural elements can be made of different building materials, such as brick, concrete and timber. A most important role in protecting the building against weather conditions, heat, vapour or noise is attributed to insulation materials whose proper selection partly depends on the type of structural system. All building components should be fully coordinated with the building's requirements determined by its purpose, its occupants and climatic conditions. The term "thermal envelope" refers to building components embracing the heated volume of a building creating a barrier, which prevents unwanted heat exchange between the interior and the exterior of the building. The efficiency of the thermal envelope depends on material composition of the walls, roof and floor, on the type and size of transparent surfaces, on solar control, air tightness, thermal bridges, etc.

In order to achieve a certain level of energy efficiency, a range of specific requirements, among which some are related to building thermal envelope, are prescribed in national building codes or standards on the basis of certificated labels widely used in construction industry. A comparison of the requirements set in the national building codes of Germany [8] and those set by Passive House Institute [10] are presented in Table 2.6.

Substantial deviations between the listed measures for the quality of the building envelope can be observed from the table above. A building can be treated as energy-efficient when its design satisfies all the requirements set in the building codes. Other standards based on certified labels, such as Minergie and Passive House, determine more stringent criteria; houses built by these criteria therefore exhibit a much better energy performance.

Table 2.6 Requirements related to the building thermal envelope set in different building codes

Building component	Reference values on the basis of EnEV [8]	Reference values on the basis of passive house [10]
Exterior walls against ambient air	$U = 0.28\ W/m^2K$	$U = 0.15\ W/m^2K$
Exterior walls and floor slabs adjacent to the ground, walls and floor slabs against unheated space	$U = 0.35\ W/m^2K$	$U = 0.15\ W/m^2K$
Roof, top floor ceiling, knee walls in attics	$U = 0.20\ W/m^2K$	$U = 0.15\ W/m^2K$
Windows	$U = 1.30\ W/m^2kg \geq 0.60$	$U = 0.80\ W/m^2kg \geq 0.50$
Roof windows	$U = 1.40\ W/m^2kg \geq 0.60$	$U = 0.80\ W/m^2K \geq 0.50$
Entrance door	$U = 1.80\ W/m^2K$	$U = 0.80\ W/m^2K$
Airtightness of the building envelope at a pressure differential of 50 Pa	Calculation in accordance with DIN V 4108–6: 2003–2006 [5]; with air leakage testing DIN V 18599–2: 2007–2002 [6]; by class I	0.6

The following subsections contain presentation of the components essential for the quality of the building thermal envelope.

2.5.4.1 Structural Materials and Construction Technology

Given a wide range of properties indicating applicability of different building materials for energy-efficient construction, the selection of the most suitable construction technology strongly depends on several factors. Among these, the most crucial are the building location, climatic conditions, availability of construction technologies and materials. With respect to climatic conditions, massive construction is more appropriate than lightweight construction for hot and dry climates, since thermal mass plays an important role in prevention of overheating. It could be claimed that timber construction is most appropriate for the majority of European climates, either cold or temperate with the exception of regions with hot summers. The selection is based on a combination of criteria taking into account environmental impact (life cycle analysis, mode of material production and its embodied energy), speed of construction, physical, mechanical and structural properties, potentials on recycling and reuse, etc. Timber construction distinguishes between six main structural systems and a few subsystems, all fully described in Chap. 3.

Furthermore, the use of glazing surfaces in timber structures is becoming an important issue of energy-efficient construction. Over years of development, glazing manufacturers have in fact improved their products' thermal insulation and strength properties as well as their coefficient of permeability of the total solar radiation and thus enabled the use of large glazing surfaces, primarily south-oriented, not only to illuminate indoor areas but also to ensure solar heating. It follows that such timber-glass structures represent a great potential in residential and public building construction.

2.5.4.2 Insulation Materials

The selection of the type and quantity of insulation installed in building elements depends on the climate, on the type of the construction element that has to be insulated, on construction technology and on general building properties.

The purpose of application is the criterion for the four basic groups of insulation materials providing:

- Thermal protection
- Sound protection
- Protection from moisture
- Protection from air leaking.

Certain insulating materials feature two functions at the same time, e.g., thermal and sound protection. Among the above-listed groups that of thermal insulation, i.e., protection from unwanted air infiltration and moisture has the highest impact on energy behaviour of buildings, while a comfortable living climate also depends on proper application of sound-insulating materials.

Thermal Insulation

Thermal insulation reduces the average heat flow through elements of the building thermal envelope. The thermal efficiency of insulating materials is expressed by the coefficient of thermal conductivity (λ) or by the coefficient of thermal transmittance (*U)* for composite elements. *U*-value signifies the heat flow through 1 m^2 of the wall area at a constant temperature difference of 1 K. Sufficient insulation helps to reduce the conductive heat gains into a building in the summer period and limits the conductive heat losses when the external temperature is lower than the interior temperature.

Many different materials are used for the purposes of thermal insulation. Considering their chemical composition, physical structure and resource insulating materials, they can be classified into inorganic, organic and new innovative materials presented in Table 2.7.

A range of different innovative materials (column 4, Table 2.7) are currently under development and their use is expected to increase in the future. Their biggest advantage in comparison to traditional insulating materials is smaller thickness

Table 2.7 Classification of common insulating materials, adopted from Papadopoulos [21] and Jelle et al. [16]

Inorganic	Organic	Combined	Innovative
Foamy (mineral source)	**Foamy**	Calcium silicate	Transparent insulation
Foam glass	Expanded polystyrene	Gypsum foam	Aerogels
Expanded clay	Extruded polystyrene	Wood wool	Vacuum insulation panels (VIP)
Vermiculite	Polyurethane foam		Gas-filled insulation panels (GFP)
Perlite			*Phase-change materials (PCM)*
			Thermochemical materials (TCM)
			Dynamic materials
Fibrous (mineral fibres)	**Expanded foamy**		
Glass wool	Cork (plant origin)		
Stone wool	Phenolic foam		
	Melamine foam		
	Fibrous (natural fibres)		
	Sheep wool		
	Cotton wool		
	Flax		
	Cellulose		
	Coconut fibres		
	Wood fibres		
	Straw		
	Hemp		

that can provide even better insulation features. Although not being typical insulating materials, PCM and TCM are mentioned due to their role in thermal storage. More information on innovative insulating materials and those still developing can be found in Jelle et al. [16] and Jelle [17].

Traditional insulating materials (listed in columns 1–3, Table 2.7) feature similar performance in terms of thermal conductivity whose value ranges from approximately 0.025–0.050 W/mK. On the contrary, these materials are characterized by significant differences related to their properties, such as

- Physical and mechanical properties (density, mechanical strength, fire resistance, moisture resistance, sound absorption)
- Environmental impact (primary embodied energy, carbon footprint, ability for reuse and recycling, use of additives against biological impacts, classification of their treatment as waste, etc.)
- Health aspect (dust emissions, toxicity during fire, level of health hazardous substances, etc.)
- Cost
- Area of application.

A detailed list of insulating material properties can be found in Papadopoulos [21] and Jelle [17]. Owing to the possibility of being manufactured in different densities even a single type of insulating material can have different physical properties, such as thermal conductivity, sound resistance, strength characteristics, thermal inertia. Figure 2.12 offers a graphical presentation of some common insulating materials mostly applied in the construction of energy-efficient buildings.

Besides thermal conductivity and density, the specific heat capacity (c) of each material composing the building envelope is crucial for the dynamic response of a building. These properties influence the time interval, also called *time lag*, between

Fig. 2.12 Graphical presentation of different insulating materials

the moment when the highest temperature appears on the external building's surface and the moment when the highest temperature is reached on the internal surface. In practice, the term *phase shift*, measured in minutes per centimetre of the material, is commonly used to describe how fast the heat will progress through the material [min/cm]. With elements composed of more materials, the phase shift can be recalculated to express an overall temperature time lag. In order to store more heat and achieve a longer time lag, materials composing external building elements need to have high heat storage capacity and high density. The recommended value for the time lag in most of European climatic regions is around 12 h or slightly more. This property reflecting thermal stability of buildings is particularly important in summer to prevent overheating. For example, if the highest temperature appears on the external building's surface at 2 pm in summer, the highest temperature of the interior appears in 12 h, at 2 am when the external temperatures are usually lower and the cooling of the interior can be thus performed through natural window ventilation.

A comparison of different insulating materials (Table 2.8) shows excellent properties of cellulose which has low thermal conductivity ($\lambda = 0.035$–0.040 W/mK), high heat capacity ($c = 1900$ J/kgK) but relatively low density (30 to 60 kg/m^3) in comparison to other standard insulating materials. Wood-fibre boards have slightly higher thermal conductivity ($\lambda = 0.045$–0.055 W/m^{2}K) but even higher heat capacity ($c = 2100$ J/kgK). Along with their density (190 do 270 kg/m^3), wood-fibre boards achieve up to 6 times longer phase shifts than other materials.

Due to the different heat storage capacities, it is also sensible to use different types of insulation materials in a single building. In order to achieve a longer phase shift, insulation materials of higher density and higher heat storage capacity are recommended for the protection of the parts of the building envelope that are extremely exposed to solar radiation, such as south-oriented roofs and façades.

Another important property of insulating materials is resistance to vapour diffusion (μ) which needs to be as low as possible. The latter characteristic along with the thickness of the material provides data on the resistance of vapour passage through a certain material [Sd in metres]. *Sd* value reveals the air layer thickness, i.e., the resistance of the air layer through which water vapour needs to permeate,

Table 2.8 Physical and mechanical properties of different insulating materials; adopted from Papadopoulos [21]

Insulating material	Thermal conductivity λ [W/mK]	Density ρ [kg/m^3]	Heat capacity c [J/kgK]	Phase shift [min/cm]	Resistance to vapour diffusion μ
Glass wool	0.030–0.045	13–100	840	7–10	1
Stone wool	0.033–0.045	30–180	840	10–19	1
EPS*	0.029–0.041	18–50	1,260	8–15	25–60
Wood fibres	0.045–0.550	190–270	2,100	42–50	10
Cellulose	0.033–0.040	30–60	1,900	18–28	1

* Expanded polystyrene

e.g., $Sd = 1$ m is equivalent to the resistance of the air layer with a thickness of 1 m. Organic foamy materials, expanded polystyrene, extruded polystyrene and polyurethane foam have relatively high resistance to vapour diffusion. In the case of diffusion-open construction that has been currently gaining in popularity, such insulating materials can either not let water vapour penetrate at all or allow for its passage only to an extremely low degree. As a consequence, condensation layers reducing the insulation capacity of the materials may appear on their surface. Using these materials to insulate timber structures means a risk of excessive condensation where humidity is forced into wood, thus leading to the growth of fungi which destroy both, wood and the insulation material. On the other hand, insulating timber structures with low-diffusion resistance materials permit a natural passage of water vapour through the building envelope. Another advantage of thermal insulating materials mainly based on wood (wood-fibres boards, cellulose) is seen in water vapour being temporarily—until the drying out is reached—distributed within a fairly large insulation area, which does not significantly alter thermal insulation properties.

For the purposes of energy-efficient building design most appropriate insulating material should therefore feature low thermal conductivity, high thermal storage capacity, relatively high density and low resistance to vapour diffusion. Such materials can be applied to above-the-ground construction elements, such as roof and walls. In the summer period, the roofs are more exposed to solar radiation than the walls, mainly due to their inclination angle and to the absence of shading elements in their surroundings. Therefore, proper roof insulation with a high phase shift is vitally important in prevention of overheating. Owing to smaller differences between the internal and ground temperatures, the phase shift is not as important for construction elements adjacent to the ground, such as a slab on grade, a basement slab and wall, whose thermal conductivity values need not exceed the average. The insulating material installed in a slab on grade, a basement slab or a basement wall is required to have relatively low thermal conductivity, but high density and high resistance to humidity and vapour diffusion. Materials with such properties are extruded polystyrene, foam glass granulate and expanded clay aggregate.

Apart from the physical and mechanical properties, environmental and health aspect should also be considered in the process of sustainable building design. Table 2.9 presents the main environmental factors of different insulating materials.

The importance of the properties described in this section is relevant not only to insulating materials but also to all the other building materials installed in a building. Since the current book treats timber-glass buildings with two major building materials, timber and glass being already predefined, the emphasis relating to the selection of appropriate building materials should be directed mainly to insulating materials, with a special focus laid on sheathings, plastering, foils, etc. In combination with timber and glass, these materials have to display optimal performance in order to achieve a high level of the building's energy efficiency and a comfortable indoor climate.

Table 2.9 Environmental properties of different insulating materials adopted from Papadopoulos [21] and Hammond and Jones [14]

Insulating material*	Primary embodied energy [MJ/kg]	Primary embodied energy [MJ/kg]	Embodied Carbon*** [kg CO_2/kg]	Reuse and recycle	Waste disposal
Glass wool	28–41	28.0–40.0	1.35	Not reusable not recyclable	No limitations
Stone wool	16	16.8	1.05	Not reusable not recyclable	No limitations
EPS**	89–105	109.2	3.40	Reusable recyclable	Long bio persistence as a waste material
Wood fibres	20	10.8–20.0	to 0.98	Reusable recyclable	Biodegradable in landfill
Cellulose	3.5	3.3	−2.00	Highly recyclable	

* Minor deviations in values can appear due to different implementations (density) of individual insulating materials and to variable data sources
** Expanded polystyrene
*** Embodied carbon (cradle-to-grave)

2.5.4.3 Glazing Surfaces

As a transparent component of the building skin, glazing surfaces can be found in windows and doors or as glass roofs and glass façades. Providing daylight and ensuring visual contact between the interior and the exterior are the main functions of the glazing, in addition to weather protection, thermal protection, noise protection and natural ventilation in the case of operable windows.

Within the concept of energy-efficient building, glazing surfaces have to be designed to suit the needs of saving energy. The heating and cooling energy requirements of a building are largely determined by heat losses and gains through the building envelope which consists of transparent and non-transparent building elements. Since the average *U*-value of the glazing is usually higher than that of other non-transparent building elements, glazing surfaces present a potential risk of the highest heat transmission losses. On the other hand, glazing areas enable solar radiation to enter the building, which is a basis for the passive solar building design. The amount of solar gains has to be controlled to prevent overheating in warm periods of the year, and an integrated shading design is therefore necessary. Only the contemporary insulating glass units can assure appropriate energy exchange satisfying the requirements of energy-efficient building design.

In order to understand the principal glazing functions and compare different glazing structures, knowledge of material properties of glass and understanding of the basics of building physics is required. These topics are presented in Sect. 4.2.

Moreover, the importance of the glazing orientation and its size is analysed in the studies contained in Sect. 4.3.1.

2.5.4.4 Solar Control

Solar control strategy design calls for identification of a situation in order to establish whether the solar input is desired or needs to be excluded. Solar control requirements mainly depend on the climate, time of the year and the characteristics of the location. For instance, the winter period when solar penetration into buildings is desired and the summer period when it should be reduced to avoid overheating are two diametrically opposite situations typical of moderate climates. Measures suitable for cold climates where solar radiation is more or less desired differ from those applicable in the case of hot climates where the excess solar radiation entering a building might increase the cooling load and make the prevention of direct solar heat gain necessary for a longer period of the year. The time of the year along with the orientation of the exposed windows requires a specific shading approach. While shading design of windows facing the equator (southward in the northern hemisphere and northward in the southern hemisphere) tends to be simple, it is far more complicated to shade eastern and southern façades. There is almost no need for shading north-oriented windows whose exposure to direct solar radiation is almost nonexistent, with the exception of early summer morning and late evening sun. Effective solar control can also prevent uncomfortable glare which can appear in any of the above-mentioned situations. Solar rays at low altitudes are likely to cause even more glare problems than the heat gain.

In order to develop a proper shading strategy, it is essential to understand the basics of solar geometry (cf. Sect. 2.4.1). The apparent movement of the sun during a day and during a year calls for a complex shading approach which can be best achieved with a combination of different strategies. Sources of solar radiation requiring shading are direct radiation and radiation reflected from the surroundings (Fig. 2.13).

Solar penetration through glazing surfaces can be reduced by means of different measures, such as shading devices among which only the external ones prove to be effective, landscaping or also glass coatings [2]. An important role within a shading strategy is furthermore played by vegetation, the surrounding buildings, structures, hills and slopes. Each of the listed measures has its advantages and is more or less appropriate for one of the orientations.

Shading with vegetation to protect low-rise buildings is effective only if broad-leaved trees are planted, since they block the sun in the summer and let it through their bare crowns in wintertime. A further important element is seen in the positioning and the height of the crowns. If shading is desired on the eastern and western building façades, where the solar incidence angle is always low, the trees should have low crowns and be placed at a certain distance from the building (Fig. 2.14).

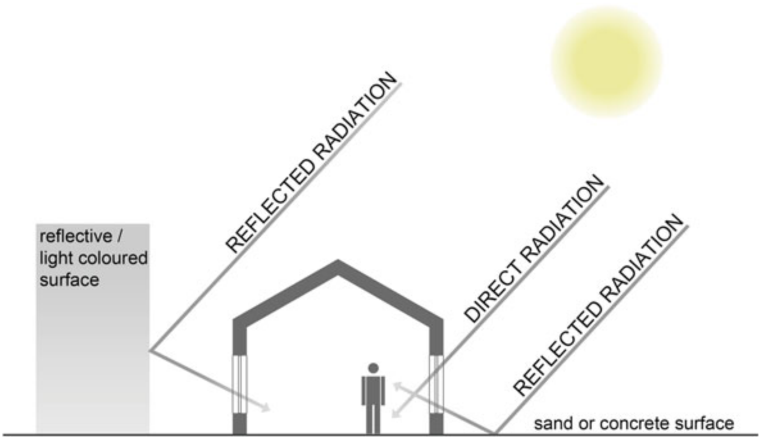


Fig. 2.13 Sources of solar radiation requiring shading

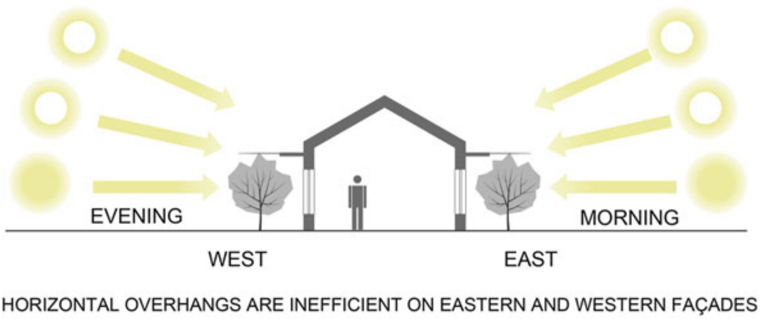


Fig. 2.14 Shading requirements for eastern and western façades

On the contrary, the best effect for the south-oriented façade is achieved if the latter is shaded with broad-leaved trees having high crowns (Fig. 2.15). Growing vines combined with pergolas can also be used for shading purposes. An additional benefit of solar control provided by vegetation is its contribution to a better microclimate while on the other hand, it is not advisable to rely solely on this strategy due to a risk of unexpected growth of a tree or its contracting a disease [2].

In addition to solar protection of the glazing surfaces, shading of pavements surrounding the building by means of shrubbery can help reduce heat absorption and subsequent heat radiation to the building and its surrounding area [2].

More reliable shading measures can be taken through external shading devices. These are more effective at reducing unwanted solar gain than internal shades and stop the sun from penetrating through the glazing. External shading devices can be fixed or operable. Fixed devices are usually cheaper but do not allow for optimal year-round adjustments to the geometry of the solar inclination angles.

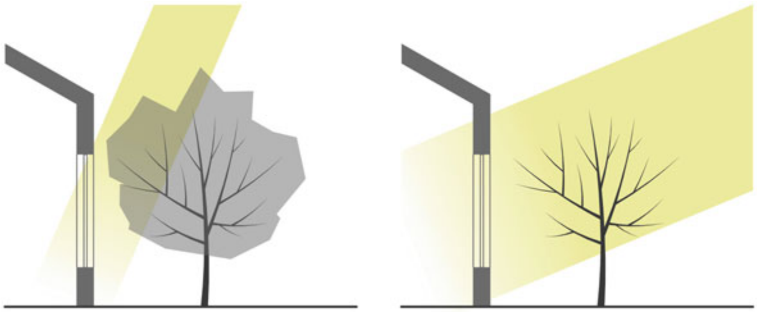


Fig. 2.15 Shading provided by vegetation

General types of external shading devices are vertical, horizontal and egg-crate devices [24], in addition to screens.

Horizontal shading elements are most suitable for southern exposures (Fig. 2.16). They are intended to reduce solar radiation of high inclination angles and are most effective when the sun position is nearly opposite to the shaded window. Best results are achieved if shading devices are installed externally, while in the case of double-skin façades, the shading elements, mostly roll-down blinds, are usually installed in the interspace between the first and the second skin.

Typical horizontal elements are roll-down blinds, shutters, louvres and overhangs. The latter can also be designed as canopies, pergolas and strips. Overhangs must be carefully planned in order to let the sun rays enter the building in winter and to reduce solar penetration in the summer period when the sun's angle of incidence is the highest (Fig. 2.17) [3].

Overhangs in eastern or western exposures need to be extremely deep to achieve the shading effect, and their use in these orientations is therefore not advisable unless a deep overhang can be used as a canopy providing a comfortable, usable outdoor space for the occupants. An adequate depth and height of the overhang can be determined with a simple calculation method which can be found at http://windows.lbl.gov/daylighting/designguide/section5.pdf [28]. Since the year-round need for shading is of a changeable nature, the use of movable shading devices proves to be a practical solution. Awnings, for example, whose function is to provide protection in the summer can be adjusted or totally folded down in the winter season.

Vertical shading devices (Fig. 2.18), such as louvers or projecting fins, are most suitable for eastern and western façades exposed to solar radiation of lower inclination angles reaching the façade from the south-eastern or south-western direction. Vertical devices also block the early morning sun coming from the north-east or the late evening sun coming from the north-west direction, which a summer period phenomenon typical of certain geographic regions (see Table 2.4). In fact, with the early morning sun of lower intensity, this type of shading serves rather as prevention from glare than from overheating.

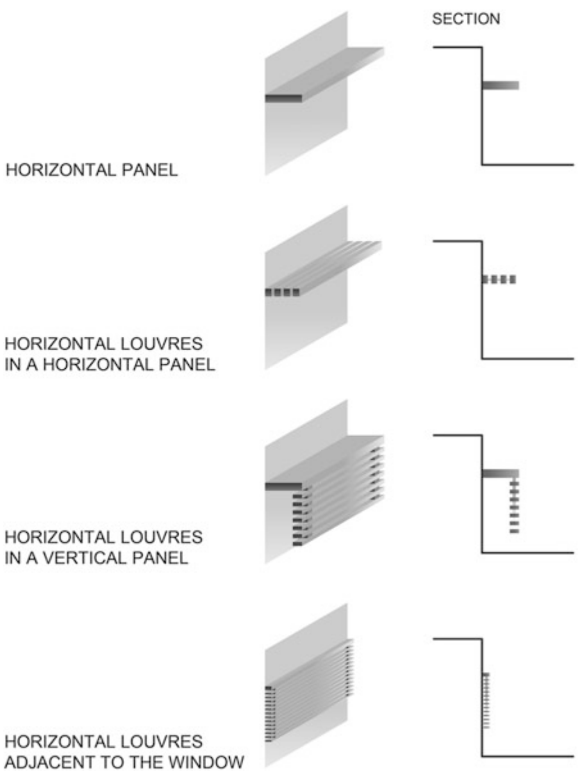


Fig. 2.16 Basic types of horizontal shading devices for southern exposures

Egg-crate devices (Fig. 2.19), like grilles made from metal, concrete or wood, are most effective for orientations which are in-between the east and south or the east and west, since they block sun rays of different altitude and azimuth angles.

Screens (Fig. 2.20) reduce solar radiation independently from the inclination angle. They can be opaque or semitransparent. A disadvantage of the screens is blocking of the view to the outside, which makes this kind of shading suitable when maximum dimming of the interior is required. Since not primarily intended for the prevention of overheating screens can be also installed on the internal side of the window.

2.5.4.5 Air Tightness

Leaking of the building envelope results in a number of problems most often arising in the winter period when cold air infiltration increases the energy demand for heating. A minor leakage problem used to be tolerated with the explanation that it contributes to fresh air exchange although the truth is that it cannot provide a sufficient quantity of fresh air and it can consequently not replace the necessary ventilation.

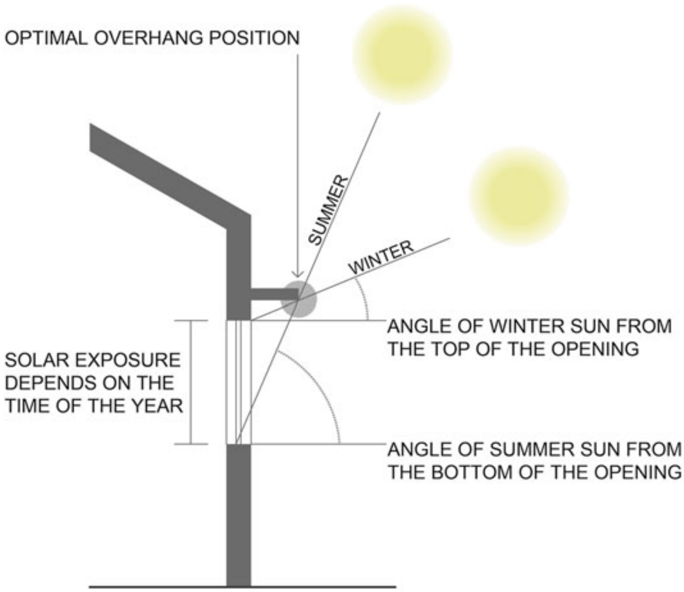
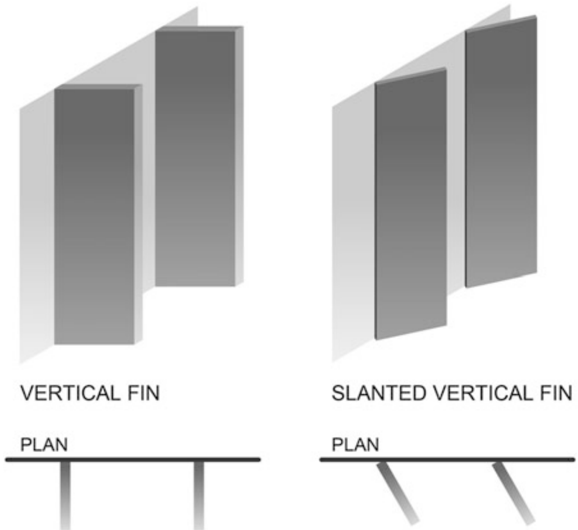


Fig. 2.17 Design strategy for overhangs in southern exposures

Fig. 2.18 Basic types of vertical shading devices for eastern and western exposures



With regard to the requirements for energy-efficient house design, the level of air tightness differs from one energy class to another. In the case of a passive house standard, where mechanical heat recovery ventilation is required, the air tightness of a building has to be excellent. The air leakage must not exceed 0.6 h^{-1} (volume per hour) at a pressure

Fig. 2.19 Egg-crate shading devices for exposures declined from the south

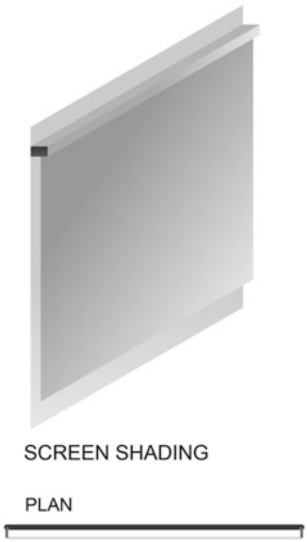


Fig. 2.20 Screen shading devices intended for the prevention of daylight in the interior

differential of 50 Pa measured by the so-called blower-door test. In houses with no mechanical ventilation system, the air tightness can be accordingly smaller. The air tightness is achieved using an airtight layer running inside the thermal envelope of a building. The appropriate materials to use for an airtight layer are internal plaster, plywood board, particle board, OSB, durability-stabilized plastic foils, bituminous felt and finally, a frequently used tear-proof building paper. Special attention has to be paid to the building element junctions, where a certain degree of air tightness has to be assured as well.

2.5.4.6 Thermal Bridge-Free Construction

Thermal bridges in building envelopes are caused by the occurrence of zones with relatively high thermal conductivity creating pathways for heat losses. Usually, these zones arise from the lack of insulation or use of highly conductive building materials or even due the specific building geometry.

Energy-efficient house design demands a reduction in thermal bridges to a minimum, which can be generally achieved by making a continuous thermal envelope with no interruption of the insulating layer (Fig. 2.21).

Windows are an exception since the thermal envelope is interrupted at the point of their placement. Nevertheless, thermal bridges can be maximally reduced if a highly insulated window is installed correctly with an airtight multiple sealing. Frequently, the most difficult thermal bridges to avoid are those of below-the-ground building elements which are affected by the soil and must be treated differently than thermal bridges to the ambient air [10].

The use of prefabricated timber-frame structural elements is a highly suitable approach in avoiding thermal bridging, which leads to reduction in heat losses and prevention of building damages.

2.6 Design of Passive Strategies

As the basic design parameters are finally determined, the second level of energy-efficient design commences. Passive design strategies allow for the passive use of natural energy sources and climatic indicators in order to ensure an adequate indoor climate and reduce the need for active heating, cooling, ventilation and

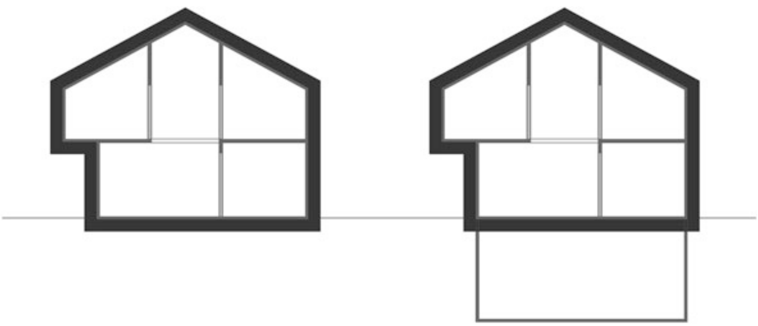


Fig. 2.21 Thermal envelope not interrupted with thermal bridges

daylighting. For example, solar radiation can be exploited to assist in reducing energy consumption for space heating and daylighting, natural ventilation can assist in reducing energy consumption for mechanical ventilation and cooling, etc.

Application of specific strategies largely depends on climatic conditions, type and occupancy of the building. The general principle is to maximize free heat gains which have to be equally distributed and stored within the building in periods with lower average outdoor temperatures and to minimize heat gains and assure natural cooling through ventilation in warm seasons. The exploitation of daylight should be part of the year-round strategy.

2.6.1 Passive Heating Strategy

The majority of European regions prove to be suitable areas for passive solar design. The key to successful passive solar design is in respecting the characteristics of the building site and its solar exposure, local landscaping, regional climate and microclimatic specifics. Solar energy can be used for heating, daylighting and water heating. While the heating of domestic water requires utilization of the equipment consuming electricity, solar heating and daylighting of interior spaces need no help of active technical systems, hence the name passive strategies.

A complex passive heating strategy integrates several approaches, e.g., solar collection, heat storage and conservation along with heat distribution [12], in addition to solar control aimed at preventing the overload of solar energy.

Solar collection in the building is essential for the passive heating strategy. The quantity of solar gain depends on the properties of elements hit by sunrays, the area and inclination of these elements, the angle of solar incidence and the available solar radiation. Furthermore, orientation, topography and shading influence the amount of solar radiation reaching the building envelope and entering the building. A number of studies have been performed with the objective to analyse the most suitable orientation, glazing size, quality and inclination angle for the best exploitation of solar radiation. A common finding of all these studies carried out for different climatic conditions is seen in their definition of southern orientation as the most effective position for solar collection. The optimal share of south-oriented glazing depends on climate and thermal properties of the building envelope. A research related to the optimal glazing size will be explained in Sect. 4.3. North-oriented glazing receives direct solar radiation only in summer, with the early morning and late evening sun, which means no gains are available in winter time when solar passive heating is most desired. East- and west-oriented windows receive a similar amount of solar radiation, with the west-facing windows contributing to overheating in summer in the case of inadequate shading. The inclination of glazing surfaces plays a further vital role relevant to the amount of solar gains. The highest transmittance of solar radiation appears when the solar beams hit the glazing perpendicular to its plane. During the summer period, the sun's altitude at solar noon ranges between 54° and 75° in most European cities and the beams hit vertical glazing at a sharp angle, which results in lower transmission and consequently in lower solar gains. Higher transmission can occur through tilted glazing installed in pitched roofs where solar beams hit the glazing plane at angles close to the perpendicular to the glazing plane. Tilted glazing therefore transfers large amounts of solar radiation in summer, with a fairly lesser degree in winter when the inclination angle of the sun is lower (between 7° and 28° for most European cities at solar noon). High gains in summer can cause overheating problems if the shading is non-efficient.

Regardless of the quantity, radiation warms the interior after it has been transmitted through the glazing. Such warming is particularly desired in the heating period when it can reduce the heating demand. Free heat gains in large-scale commercial and office buildings covered predominately in glass skin can cause an increase in the cooling demand; special attention thus needs to be paid to the quality of glazing and solar control.

One of the possible approaches to solar collection is to make use of buffer zones which are a type of intermediate sunspaces between the interior and the exterior, usually built in as glazed spaces attached to the southern side of the building. Buffer zones capture direct solar heat gain throughout the day and transfer it to the building's interior by means of natural convection when needed, which usually makes sense in the winter period for warming the interior spaces in the late afternoon and evening, when no direct solar gain is obtainable any more. It is reasonable to use low-e coatings for the glazing of the attached sunspaces in order to prevent heat losses of the long-wave IR radiation (re-emitted from floors, walls and furniture, after they have been heated by the absorbed solar energy) through the glazing back to the exterior. If necessary, sunspaces can in fact supply heat to the building even in spring and autumn but they have to be efficiently shaded in the summer period to avoid overheating (Fig. 2.22). When considering sunspaces, it is important to note that they are seldom occupied and can be therefore exposed to greater temperature variations [11].

Not only the glazing but also the opaque surfaces of the building envelope can collect heat from the sun. When solar radiation strikes the opaque building element, a part of the energy is reflected while another part is absorbed and transformed into heat. As the heat flow transfers progressively towards the internal

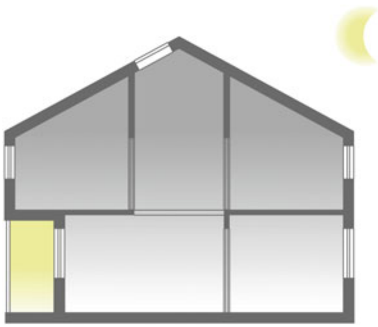


Fig. 2.22 Sunspaces can maintain a comfortable indoor temperature in winter nights

surface by means of conduction, the building element heats up. In addition to the fact that opaque elements do not allow for a direct transmission, they usually have up to three times lower heat transfer coefficient (*U*-value). The latter indicates that the amount of energy passing through the opaque building element is lower than the energy directly transmitted through the glazing.

Another important approach to passive heating strategies is the effect of heat storage in the building materials, which is aimed at retaining the collected heat in order to use it later when required [12]. The latter strategy, which is based on thermal inertia—the capacity of materials to store and release heat, uses the heat stored in the mass of the building materials, i.e., thermal mass, after being struck by solar radiation during the day. The building materials release heat when the surrounding temperature drops. In order to perform effective heat storage, the materials must exhibit higher values of density and thermal capacity. In massive buildings, the structural elements are made of dense materials with high heat storage capacity, e.g., of heavyweight concrete, brick or stone. By absorbing and storing large quantities of heat, such materials can help reduce the temperature swing in the interior spaces during the day. Apart from the above-mentioned traditional materials where the process of sensible thermal energy storage is based on the heat capacity, there exist other materials which can store heat on the basis of phase change (phase-change materials—PCM) or on the basis of chemical processes (thermo chemical materials—TCM). Either concrete or PCM can be used in the interior elements of buildings with lightweight structure, which are not capable of storing heat for a longer time period and therefore react more quickly to the external temperature change. The process of heat storage is beneficial in both, the summer and the winter periods. While it can be used to reduce the interior daytime temperature and to postpone the peak temperature in summer, the advantage of its use in winter is in storing the heat collected during the day and releasing it into space at night.

Another option besides direct heat storage is the use of more complex principles as for instance the Trombe-Michel walls or slabs with an integrated pipe system, where the energy is transferred within or between materials by a heat carrier fluid.

2.6.2 Passive Cooling Strategy

A number of different concepts for passive cooling can be applied to energy-efficient building design including solar control, adequate insulation, the effect of thermal inertia, natural ventilation and natural cooling. Some of these approaches have already been discussed in the previous parts of the text.

2.6.2.1 Heat Storage

Due to *thermal inertia,* the storage of heat and the time lag of heat flow through the building envelope can be used either for heating or for cooling the interior space. The concept is more helpful in climatic regions with significant diurnal variations in temperature. Throughout Europe, there is a relatively large air temperature diurnal swing in the summer period, with even larger swings typical of hot and dry climates. As far as cooling strategy is concerned, the temperature time lag contributes to the reduction and postponement of the interior space peak daytime temperature.

2.6.2.2 Nighttime Cooling

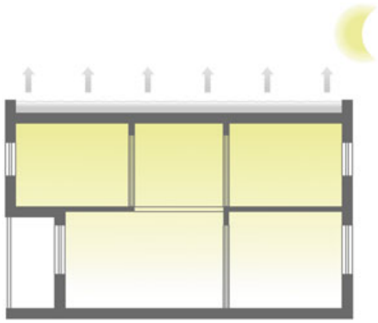
Another important impact of thermal inertia is the fact that the heat stored in building elements can be released to the outside at night, when the external air temperature is usually lower than the internal. This concept is more effective if combined with *nighttime cooling* by means of natural ventilation in order to lower the interior air temperature and precool the building structure for the following day (Fig. 2.23).

2.6.2.3 Cooling by Night Sky Radiation

When the weather is clear, air temperatures at night tend to be very low, which provides a potential for the heat stored in the building materials and roof surfaces or the water from roof ponds to be released to the sky through radiation (Fig. 2.24). This is accompanied by a significant temperature drop of water or other surfaces having radiated heat to the clear night sky. Many different techniques have been tested in order to achieve the effect of night sky radiation cooling. Some of them incorporate using water tanks or pools placed on the roof,

Fig. 2.23 Convective nighttime cooling by means of ventilation

Fig. 2.24 Radiative cooling



covered by a movable roof during the day. At clear nights, the cover is removed and the exposed water radiates heat to the sky. Such effect can be applied to solar panels where a process opposite to solar heating is used to cool the water temperature, while the electric energy is needed for pumping. Cooling with night sky radiation is less appropriate for humid climates, since humid air is less permeable for long-wave heat radiation.

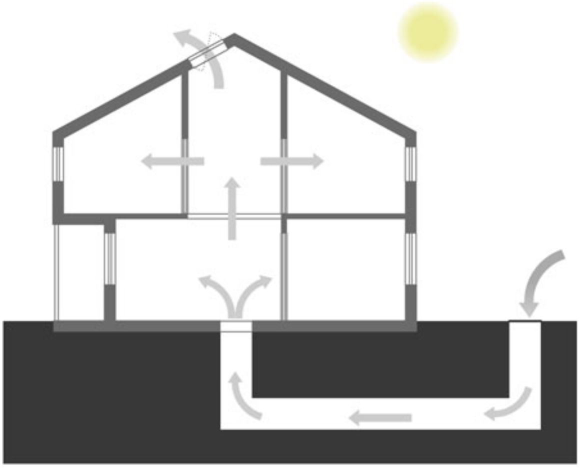
2.6.2.4 Evaporative Cooling

The concept of evaporative cooling is based on physical process where a substance absorbs the energy known as latent heat of vapourization to transform its state from liquid to gas. In the case of evaporative cooling, the heat supplied by hot air causes transformation of the water from fountains, pools and ponds, located next to the building or on its roof, to vapour. Consequently, a drop in air temperature and an increase in air humidity appear. The long-wave IR radiation process described above could also be applied in the building interior where it is necessary to control the level of humidity. However, the evaporative cooling effect cannot be applied in regions with a humid climate.

2.6.2.5 Ground Cooling

The temperature of the ground at a depth of approximately 3–4 m, which has been found to be equal to the annual mean air temperature for the location [11], might vary by ±2 °C depending on the season. The air used for ventilation of the building is cooled by a passage through the underground duct. Although it is possible to use this effect without any mechanical systems, ground cooling is more often used within active systems, where ventilation units are combined with ground pipes to precool the fresh ambient air (Fig. 2.25).

Fig. 2.25 Ground cooling



2.6.3 Natural Ventilation

Natural ventilation is primarily used to supply fresh air to the building. On average, a human being needs a minimum of 8 l of fresh air per second. An adequate fresh air provision depends on the number of persons in the room and their activity. To assure the physiological needs and to maintain the internal air quality, fresh air can be supplied either by natural or mechanical ventilation. With natural ventilation, it is necessary to control the outdoor air temperature to prevent larger infiltration heat losses or gains which could appear in case of a large difference between the interior and exterior temperature. To avoid substantial ventilation heat losses in summer and winter, the total fresh air supply is usually provided by mechanical ventilation.

As already mentioned in the previous subsection, natural ventilation is also beneficial in the summer time for the reason of ensuring thermal comfort. Significantly larger ventilation rates (80–100 l per person per second) are necessary to cool the building, which, however, depends on several factors like the external air temperature, exposure of transparent surfaces to solar radiation, internal gains, etc.

In general, natural ventilation is driven by either wind or thermal forces [11]. While the wind-driven ventilation is induced by the pressure differences, thermal circulation caused by a temperature difference between the outside and inside air induces a natural flow through the building. The direction of the flow depends on the temperatures. The air mass inside the building having a higher temperature than that of the outside air has lower density than the outside air mass and tends to move upwards, while the cooler air from the outside flows into the lower areas of the building. This type of ventilation, called "stack ventilation" or "chimney effect", is most efficient if operable windows are installed at the bottom and the top of the building (Fig. 2.26).

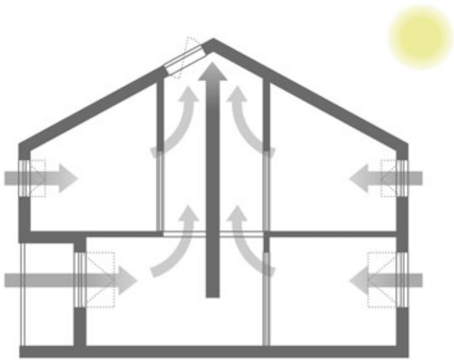


Fig. 2.26 Stack ventilation effect

Apart from air flows due to infiltration of fresh air, the appearance of the air mass flow between different areas of the building due to their different air temperature is equally possible.

On the other hand, the wind-driven natural ventilation can be provided through single-sided or cross-ventilation. Induced by a difference in the wind pressure that usually arises between the windward and the leeward sides of a building, it is most effective if the air mass is driven through the building as cross-ventilation. Single-sided ventilation is beneficial for the provision of fresh air as well, but achieves a rather lower air exchange than cross-ventilation (Fig. 2.27).

Different types of ventilation can be combined to achieve an even better effect. In regions with constant winds, the positioning of buildings has to be carefully considered. Besides the provision of fresh air, wind forces contribute to decreasing the surface temperature due to convection, which can be beneficial for cooling the building mass. If there is a need to reduce the wind impact, certain barriers made of vegetation, walls or fences should be designed at exposed areas. These can also be used to divert the wind direction and achieve better ventilation in cases where the building openings cannot be positioned on the exposed façades (Fig. 2.28).

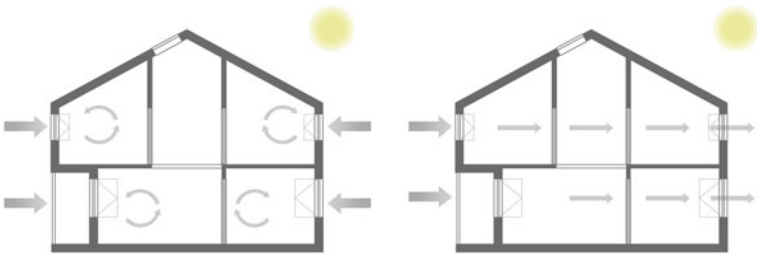


Fig. 2.27 Single-sided and cross-ventilation

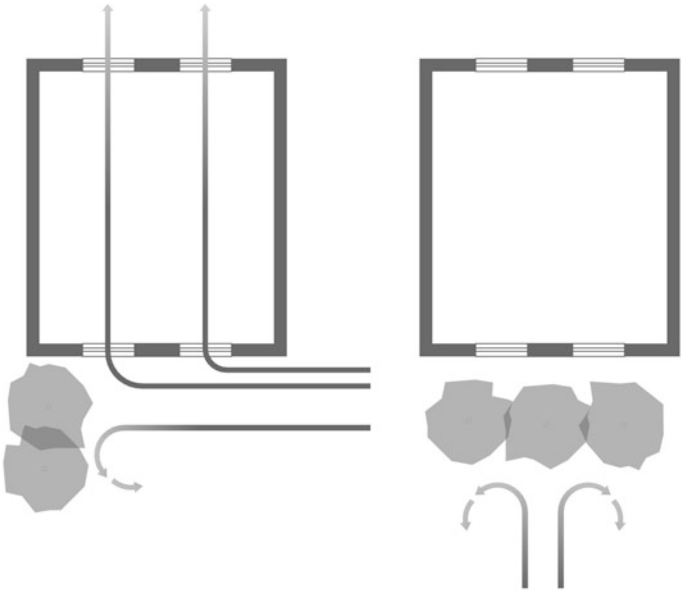


Fig. 2.28 Vegetation barriers used to the divert the wind direction where needed

2.6.4 Daylighting

Daylighting is a design strategy employing the available daytime visible light to illuminate the interior space. Daylight has been used for centuries as the primary source of light in interiors and has been an implicit part of architecture for as long as buildings have existed [26]. Nowadays, when we spend 90 % of our time indoors, adequate daylight has become even more important. Several studies have proved the value of daylight providing visual comfort benefits that are essential for improved productivity and satisfaction of the buildings' occupants. Properly applied daylighting prevents inconvenient glare effects by not allowing the sun to directly enter a space and ensures good natural illumination across the entire internal space [1]. Besides ensuring an adequate visual comfort, daylight also reduces the need for artificial electrical lighting during daytime hours.

Daylight can reach the interior space through the glazed openings in the roof or through the façade windows. The roof windows are usually limited to the top floor of a building, while the façade windows can be applied to multiple floors of a building, satisfying the requirements of correct exposure and orientation [1]. An integrative approach combining both, the roof and façade windows properly distributed in the window envelope, is advised for the achievement of optimal lighting comfort. Additionally, the openings should be equipped with shading devices for situations when daylight is too bright or when a direct sun causes glare problems.

For the purposes of daylight building design, several tools can be of assistance. One of such freely accessible tools is VELUX Daylight Visualizer 2. It is intended to analyse daylight in buildings and to aid professionals by predicting and documenting daylight levels on the one hand and visualizing a space prior to realization of the building design on the other. The daylight visualizer intuitive modelling tool permits quick generation of 3D models in which the roof and façade windows are freely inserted. The programme also enables users to import 3D models generated by CAD programmes in order to facilitate a good workflow and permit the evaluation of a wide range of building designs, in addition to offering flexibility in the evaluation process. Other features of the programme include predefined settings, a surface editor, site specifications, flexible view settings as well as multiple daylight parametrics providing accurate predictions [26]. The analysis made by VELUX Daylight Visualizer 2 is presented in Fig. 2.29.

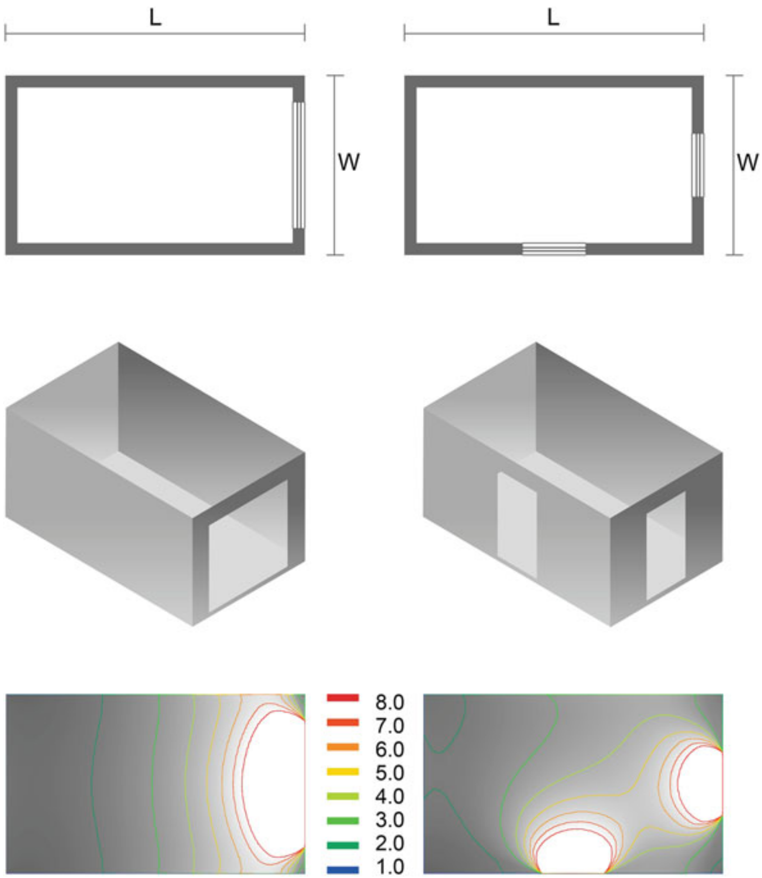


Fig. 2.29 Analysis of the daylight factor for a room with two windows

The above figure demonstrates the influence of the window openings (bright spots) exerted on the overall daylight conditions in the room.

The daylight factor, as one of the indicators the programme uses to assess daylight quality, describes the ratio between the amount of daylight available in the interior (at the height of the work plane) and the amount of non-obstructed daylight available outside under standard CIE overcast sky conditions. It is expressed as a percentage [15].

The daylight factor is common and easy to use measure for the available amount of daylight in a room. It can be measured for a specific point or expressed as an average. The latter is the arithmetic mean of the sum of point measurements taken at a height of 0.85 m in a grid covering the entire floor area of the room. The higher the DF, the more daylight is available in the room. An average DF below 2 % generally makes a room look dull and electrical lighting is likely to be frequently used. Rooms with an average DF of 2 % or more can be considered day lit, but electrical lighting may still be needed to perform visual tasks. A room will appear strongly day lit when the average DF is above 5 %, in which case electrical lighting will most likely not be used during daytime [4].

2.7 Active Technical Systems

Besides passive building components presented in previous subsections, active technical systems are necessary for a complex integrated building operation. Active technical systems refer to heating, ventilation and air conditioning (HVAC), domestic hot water supply, artificial lighting and renewable energy systems. They all need to consume electrical power for their performance. With the exception of lighting, these processes can be classified as mechanical systems. A way to improve the overall efficiency of contemporary mechanical systems is to incorporate strategies that use surrounding natural conditions like outdoor air, solar radiation, the ground or groundwater.

An example of such strategy can be demonstrated by the energy recovery ventilation system. In energy-efficient houses, it is necessary to combine natural and mechanical ventilation to ensure suitable indoor air quality. In order to minimize ventilation heat losses, a heat recovery system (HRV) can help make mechanical ventilation more effective by reclaiming energy from exhaust airflows. The system uses the conditioned exhaust air to precondition the incoming fresh air that needs to be heated or cooled. Both, the exhaust and fresh air pass through a heat exchanger where the incoming air is preheated or cooled by the energy of the exhaust air, thereby reducing the amount of conditioning needed. In a typical system configuration, air is supplied to the living room, dining room and bedrooms while it is removed from the kitchen, bathroom and toilets.

Electricity consumption can be minimized by the use of highly efficient systems, in addition to energy-efficient household appliances, light bulbs and luminaire. The use of photovoltaic panels (PV) intended for the production of electrical energy are a further improvement of the overall energy balance.

With efficient renewable energy systems, such as heat recovery systems, heat pumps, solar panels, photovoltaic panels, etc., providing ventilation, space heating, domestic water heating and even electricity, the building uses less or even no fossil fuel for its operation, which leads to lower environmental burdening.

The main goal of energy-efficient house design is to reduce the overall energy use in the building primarily through designing the optimal building shape, orientation and building components as well as by optimizing passive strategies. The next stage is to adapt the specific energy-efficient technical systems to the existing building design. Since none of these strategies will result in maximum efficiency without the cooperation of the buildings' owners, operators and occupants, it is important to educate all the participants on the proper use of energy-efficient buildings and their technology. With respect to all these parameters, energy-efficient building design is understood as an extremely complex process which demands an accurate approach in planning and selecting each of the individual parameters.

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