Climatic conditions

Weather is the state of the atmosphere, to the degree that it is hot or cold, wet or dry, calm or stormy, clear or cloudy. Most weather phenomena occur in the troposphere, just below the stratosphere. Weather refers, generally, to day-to-day temperature and precipitation activity, whereas climate is the term for the average atmospheric conditions over longer periods of time [1]. For energy uses in buildings weather conditions play an important role. For this reason it is important to define the proper boundary conditions in terms of the different parameters affecting energy and comfort in buildings, which may be different from case to case depending on the particular problem.

Atmospheric temperature is a measure of temperature at different levels of the Earth's atmosphere. It is governed by many factors, including incoming solar radiation, humidity and altitude. When discussing surface temperature, the annual atmospheric temperature range at any geographical location depends largely upon the type of biome, as measured by the Köppen climate classification (see Figure 1):

- GROUP A: Tropical/megathermal climates
- GROUP B: Dry (arid and semiarid) climates
- GROUP C: Temperate/mesothermal climates
- GROUP D: Continental/microthermal climate
- GROUP E: Polar climates
- GROUP H: Alpine climates

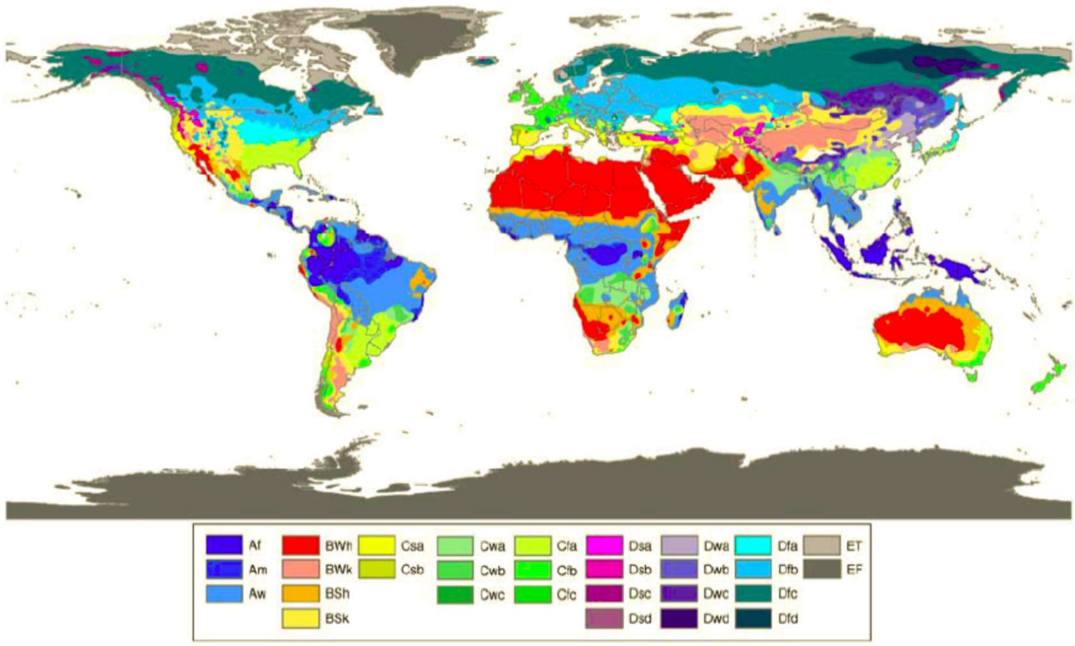


Figure 1: Köppen classification for climates
Source: [2]

Nowadays climatic data are available for most of the climates. Weather conditions can be define by the following parameters:

- Design heating temperature
- Design cooling temperature
- Degree day
- Mean monthly temperatures
- Hourly values
- Test Reference Year

Outdoor temperature

Design heating temperature

The design temperature for heating conditions is usually an extreme temperature which might occur in the heating season. Usually the design conditions assume a suitable number of days under constant climatic conditions, i.e. at the design temperature and with no solar radiation, so as to assume steady state conditions through the envelope. In the table 1 the dry-bulb temperatures corresponding to 99.6% and 99.0% annual cumulative frequency of occurrence of some World locations are reported. In the same table the month when the minimum temperature occurs is listed as well.

Design cooling temperature

The design temperature for cooling conditions is usually an extreme temperature which can occur in the cooling season. Usually the design conditions assume a suitable number of days repeating the same climatic conditions. The design day assumes a certain hourly profile of outdoor temperatures with clear sky conditions. In table 1 the dry-bulb temperature corresponding to 0.4%, 1.0%, and 2.0% annual cumulative frequency of occurrence and the mean coincident wet-bulb temperature of some World locations are reported. In the same table the month when the maximum temperature occurs is listed as well. The cyclic conditions of the design day can be calculated, once known the maximum temperature ($T_{amb,max}$) and the temperature difference between the minimum and maximum temperature (Δt_{amb}) by means of the following equation:

$$t_{amb,h} = t_{amb,\max} - p_h \Delta t_{amb} \qquad (1)$$

where p_h is a coefficient depending on the considered time hour; its hourly value is listed in Table 2.

Table 1: *Design winter and summer conditions of some cities around the World*

	Heating coldest month			Cooling hottest month			
	[n]	DB 99.6% [°C]	DB 99.0% [°C]	[n]	DB Range [°C]	DB 4% [°C]	WB 4% [°C]
Abu Dhabi	1	11.5	12.9	8	12.5	44.9	23.2
Athens	2	1.6	3.1	8	9.1	35.1	21.1
Auckland	7	1.8	2.9	2	6.9	25.2	19.7
Bangkok	12	19	20.4	4	9.2	37.2	26.7
Beijing	1	-10.8	-9.1	7	8.9	34.9	22.2
Berlin	2	-11.8	-10.8	7	9.2	30	18.9
Buenos Aires	7	-0.1	1.3	1	11.8	33.7	22.5
Cairo	1	7.7	8.7	7	11.5	38.1	21.1
Cape Town	7	3.8	5	2	9.5	31	19.4
Caracas	2	20.7	21.2	9	7.2	33.4	28
Chicago	1	-20	-16.6	7	10.5	33.3	23.7
Dakar	2	16.5	16.9	9	5.1	32.1	23.5
Debrecen	1	-13.8	-10.9	7	11.1	7.7	21.3
Helsinki	2	-22.8	-19.1	7	9.5	26.7	17.9
Houston	1	-1.6	0.5	7	10.1	36	24.8
Lima	8	14	14.6	2	6.3	29.3	23.6
London	2	-4.6	-3	7	9.7	27.2	18.7
Melbourne	7	2.8	3.8	2	11.6	34.6	18
Mexico City	1	4.1	5.6	5	13.8	29	13.8
Montreal	1	-23.7	-21.1	7	9.3	30	22.1
Moscow	2	-23.1	-19.8	7	8.3	28.4	20.1
Mumbai	1	16.5	17.8	5	5.6	35.8	23
Nairobi	7	9.8	11	3	11.9	29	15.7
New Delhi	1	6.3	7.3	6	9.7	42	22.2
New York	1	-10.7	-8.2	7	7.4	32.1	23.1
Paris	1	-5.9	-3.8	7	10.1	30.9	20.1
Phoenix	12	3.7	5.2	7	12	43.4	21.1
Riyadh	1	5.9	7.2	7	13.5	44.2	18.7
Salt Lake City	1	-12.6	-9.9	7	14.4	36.3	17.5
San Paulo	7	8.9	10	2	8.2	32.1	20.4
Seville	1	1.3	2.9	7	16.4	39.9	23.8
Sidney	7	6	7	2	6.5	32.8	19.6
Singapore	12	23	23.5	6	5.5	33.2	26.4
Stockholm	2	-17.8	-14.2	7	9.4	27.1	17.5
Strasburg	1	-9.8	-7	7	11.1	31.1	20.9
Tehran	1	-2.8	-1.3	7	10.6	38.5	19
Tokyo	1	-6.9	-5.1	8	7.7	32.1	26
Vancouver	12	-7	-4	8	7.6	25	18.2
Venice	1	-4	-2.8	7	8.8	31.1	23.5
Washington DC	1	-10.6	-8.2	7	10.4	34.4	23.9

Table 2: Values of p_h coefficient to be used in equation (1) for each hour of the day

hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
p_h	0.87	0.92	0.96	0.99	1	0.98	0.93	0.84
hour	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
p_h	0.71	0.56	0.39	0.23	0.11	0.03	0	0.03
hour	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
p_h	0.1	0.21	0.34	0.47	0.58	0.68	0.76	0.82

Degree day

Degree days (DD) are essentially a simplified representation of outside air temperature data. They are widely used for calculating the effect of outside air temperature on building energy consumptions.

Heating Degree Days (HDD) are a measure of how much (in degrees), and for how long (in days), outside air temperature was lower than a specific base temperature or balance point. They are often used for calculations related to energy consumption required to heat buildings.

Cooling Degree Days (CDD) are a measure of how much (in degrees), and for how long (in days), outside air temperature was higher than a specific base temperature. They are often used for calculations relating to the energy consumption required to cool buildings.

Weather normalization of energy consumption is one of the most common uses of DD. It enables a comparison of energy consumption from different periods or places with different weather conditions. Depending on the availability of outdoor temperature data, different methods can be used for calculating HDD and CDD. The hourly or ideal method, produces the most accurate estimate, however it requires the availability of very detailed climate data, not always available for each location of interest. According to the ASHRAE daily mean temperature method, the daily degree days are the difference between the daily mean temperature $\bar{t}_{amb,d,j}$ and the internal base temperature T_i, when they are below a certain base outdoor temperature (for heating) or above a certain outdoor temperature (for cooling). The base outdoor temperature named $t_{threshold,heating}$ is the outside temperatures above which the building does not require heating. The base outdoor temperature named $t_{threshold,cooling}$ is the outside temperatures below which the building does not require cooling. Hence the calculations for Heating Degree Days (HDD) and Cooling Degree Days (CDD) are given by equations (2.a) and (2.b):

$$HDD = \sum_{j=1}^{365}(t_i - \bar{t}_{amb,d,j}) \qquad \text{if } \bar{t}_{amb,d,j} < t_{threshold,heating} \qquad (2.a)$$

$$CDD = \sum_{j=1}^{365}(t_i - \bar{t}_{amb,d,j}) \qquad \text{if } \bar{t}_{amb,d,j} > t_{threshold,cooling} \qquad (2.b)$$

There are different ways to choose the inner temperatures and the threshold temperatures since different buildings have different base temperatures [8].

As an example, in Table 3 the *HDD* and the *CDD* considering T_i = 18°C and $T_{threshold}$ = 10°C for both heating and cooling is shown. It has to be underlined that the choice of the inner temperature can be different for heating and cooling as well as the choice for threshold outdoor temperature. As an example, in a recent paper Carnieletto et al. [9] used The inner baseline temperature (T_i) has been settled, for both heating and cooling conditions, equal to 18°C and a threshold for the external temperature (Tt) was set equal to 14°C in HDD calculation and equal to 20°C for the CDD evaluation.

Table 3: Winter and summer degree days of some cities around the World

		Heating DD		Cooling DD	
		18°C	**10°C**	**18°C**	**10°C**
1	**Abu Dhabi**	24	0	6254	3358
2	**Athens**	1112	82	2966	1076
3	**Auckland**	1163	0	1909	131
4	**Bangkok**	0	0	6757	3837
5	**Beijing**	2906	1420	2199	765
6	**Berlin**	3156	1191	1125	170
7	**Buenos Aires**	1189	0	2524	663
8	**Cairo**	307	0	4472	1859
9	**Cape Town**	868	0	2388	326
10	**Caracas**	0	0	6002	3082
11	**Chicago**	3430	1748	506	1743
12	**Dakar**	1	0	5151	2231
13	**Debrecen**	3129	1313	279	1384
14	**Helsinki**	4721	2336	577	33
15	**Houston**	774	134	1635	3915
16	**Lima**	114	0	3541	735
17	**London**	2886	778	864	32
18	**Melbourne**	1733	127	1525	210
19	**Mexico City**	547	0	2503	131
20	**Montreal**	4493	2525	1185	234
21	**Moscow**	4655	2498	862	99
22	**Mumbai**	0	0	6219	3299
23	**Nairobi**	243	0	2870	193
24	**New Delhi**	278	0	5363	2721
25	**New York**	2627	1052	639	1984
26	**Paris**	2644	791	1209	142
27	**Phoenix**	543	28	2661	5066
28	**Riyadh**	305	0	5915	3301
29	**Salt Lake City**	2908	1200	669	1881
30	**San Paulo**	293	1	3483	854
31	**Seville**	927	19	3031	1020
32	**Sidney**	687	5	2871	634
34	**Singapore**	0	0	6374	3454
35	**Stockholm**	4239	1965	683	36
36	**Strasburg**	2947	1054	1162	136
37	**Tehran**	1749	577	1482	3230
38	**Tokyo**	2311	794	1911	508
39	**Vancouver**	3020	901	806	5
40	**Venice**	2262	762	1906	526
41	**Washington DC**	2478	993	730	2164

Usually in most of the European countries the HDD is quite well established, while the CDD definition is not always clear. In many countries (e.g. Italy and Germany) the reference threshold base temperature for heating condition is fixed at 12°C. The indoor reference indoor temperature depends on the building, but usually it can be considered equal to 20°C. The heating degree day (*HDD*) can be calculated in an easier way as the difference between the indoor temperature and the mean outdoor monthly temperature $\bar{t}_{amb,m,z}$ times the number of days of the considered month $n_{d,z}$:, if the considered z_{th} month has an average temperature lower than 12°C:

$$HDD = \sum_{z=1}^{12} \left[\left(t_i - \bar{t}_{amb,m,z} \right) \cdot n_{d,z} \right] \tag{3}$$

In Figure 2 the graphical meaning of the degree day is shown considering 20°C as reference indoor temperature. As can be seen the degree day is the light green area between the indoor temperature and the outdoor mean monthly temperature; the wider the green area (i.e. the higher the degree day), the colder the climatic conditions.

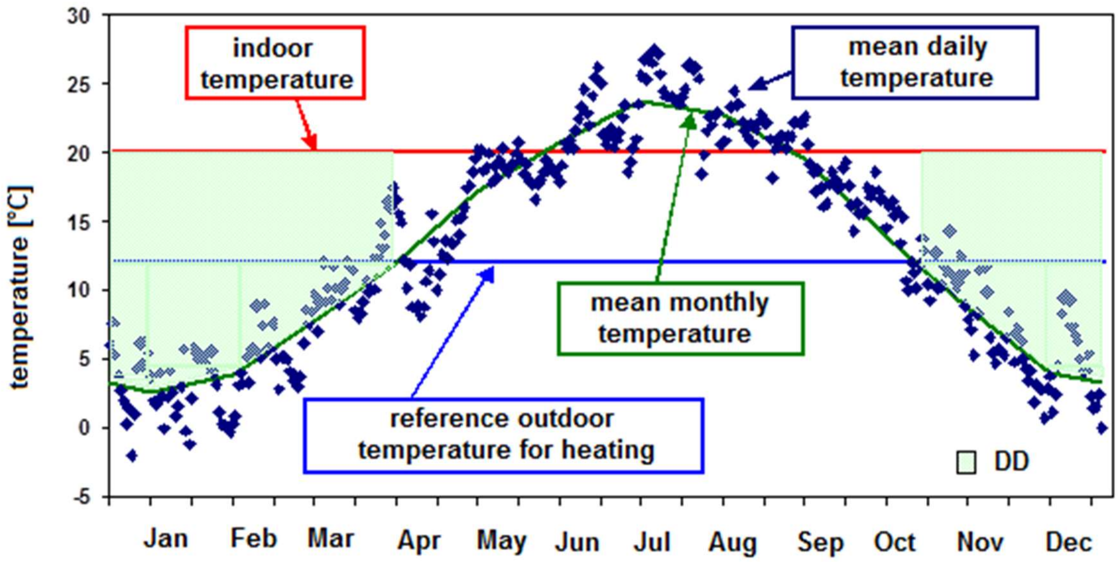


Figure 2: Graphical representation of the Heating Degree Days (HDD) of a typical year in Venice for an indoor temperature of 20°C and a threshold temperature for the outdoor air $T_{threshold,heating}$ = 12°C

Mean monthly temperatures

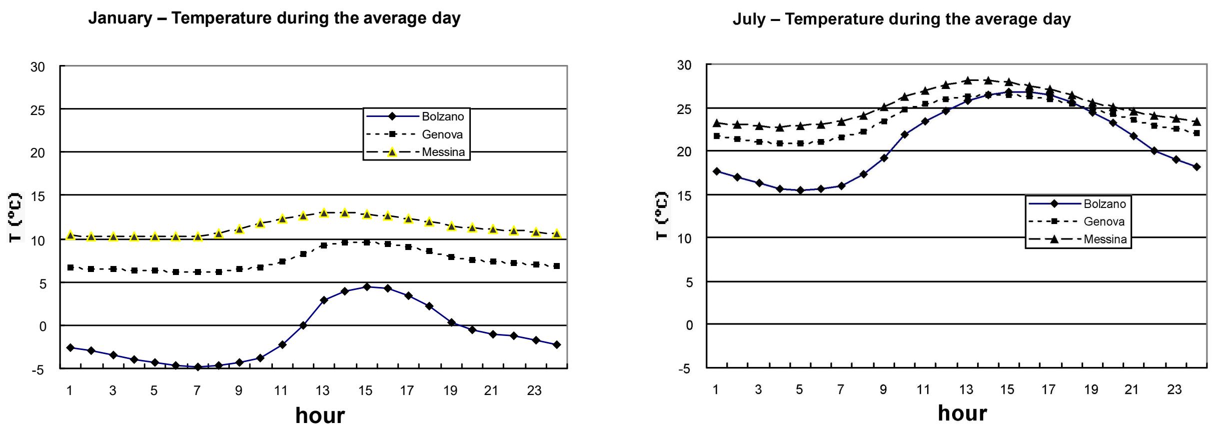
Mean monthly temperatures define the mean temperatures of each month of the year. They may be shown together with the maximum mean value and the minimum mean value of the month. In any case, for energy purposes the average outdoor temperature of the month is sufficient to determine many physical phenomena which may happen in a building.

As will be shown afterwards, the average outdoor temperatures may be used for evaluating the net energy demand of a building by means of the quasi-steady state method. The average value of outdoor temperature may be used also for determining the average water vapour content inside a building, as well as for checking moisture problems on internal surfaces of the envelope and interstitial condensation problems inside wall structures.

Profile of hourly average temperatures of the month

The profile of the hourly average temperatures of the month can be used for several purposes. It might be used for determining the energy demand of buildings for both heating and cooling.

If the monthly values are not known the hourly trend of temperatures can be built up by using the average values of the outdoor temperature and the mean values of minimum and maximum temperatures. Please note that the peak loads determined via the mean day hourly patterns do not represent the peak power for heating and cooling, which have to be calculated via design conditions.



a **b**

Figure 3: Average monthly temperatures for Bolzano (North Italy, mountain area), Genua (North Italy, coast climate), Messina (South Italy, coast) for the coldest month (a) and the warmest month (b) of the year

Test Reference Year

The Test Reference Year (TRY) is the hourly average profile of outdoor temperature of one typical year. The TRY is built up based on at least 20 years. The TRY is built up by calculating the mean outdoor temperature. The real occurred month which presents outdoor conditions which are the closest to the average value of the series is chosen to be representative of real conditions. Real hourly values over the month are used for building the TRY, since the combination of solar radiation and temperature may lead to errors in the evaluation of energy demand of the building. Therefore it is assumed that the most suitable trend of outdoor weather for determining the energy heating/cooling demands is based on real happened conditions. The use of artificial weather data may lead to mistakes, therefore, in case of few data for the climatic conditions, it is preferable to use average monthly data, instead of random profiles reconstructing TRY.

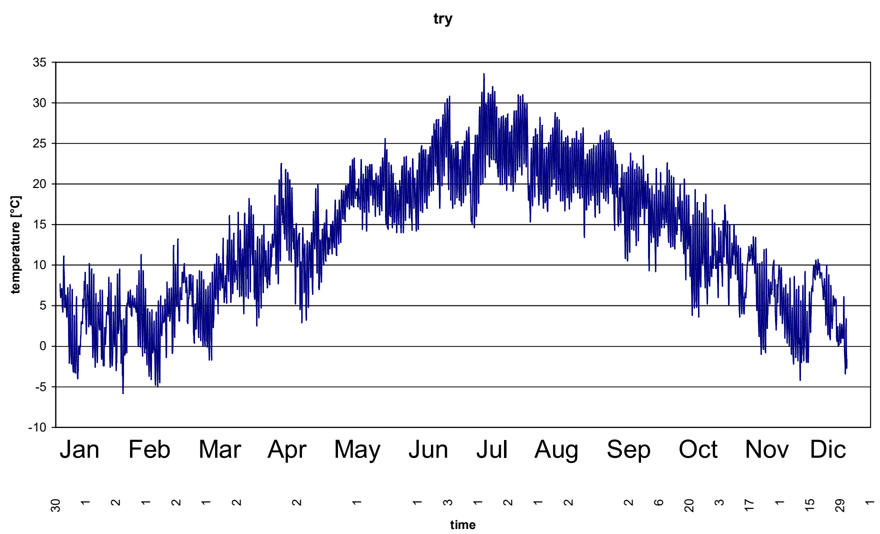


Figure 4: Temperature profile of the Test Reference Year (TRY) of Venice

Solar radiation

The spectrum of the Sun's solar radiation is close to that of a black body with a temperature of about 5800 K. The shape of the spectrum of energy emitted by a body is expressed by the well known Wien law which gives the peak in wavelength depending on the temperature of the radiative surface (Figure 5):

$$\lambda_{max} = \frac{2898}{T} \tag{4}$$

The Sun emits electromagnetical radiation across most of the electromagnetic spectrum, emitting X-rays, ultraviolet, visible light, infrared, and even Radio waves.
The spectrum of electromagnetic radiation striking the Earth's atmosphere spans a range of 100 nm to about 1 mm. This can be divided into five regions in increasing order of wavelengths:

- Ultraviolet C (UVC) range, which spans a range of 100 to 280 nm. The term ultraviolet refers to the fact that the radiation is at higher frequency than violet light. Due to the absorption by the atmosphere very little reaches the Earth's surface.
- Ultraviolet B (UVB) range spans 280 to 315 nm. It is also greatly absorbed by the atmosphere, and along with UVC is responsible for the photochemical reaction leading to the production of the ozone layer.
- Ultraviolet A (UVA) spans 315 to 380 nm.
- Visible range or light spans 380 to 780 nm.
- Infrared range that spans 780 nm to 1 mm. It is responsible for an important part of the electromagnetic radiation that reaches the Earth. It is also divided into three types on the basis of wavelength:
  - Infrared-A: 780 nm to 1,400 nm
  - Infrared-B: 1,400 nm to 3,000 nm
  - Infrared-C: 3,000 nm to 1 mm.

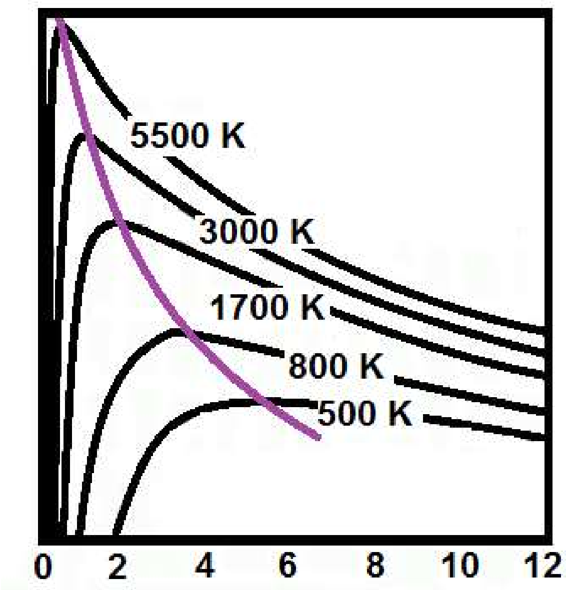


Figure 5: Radiation emission as a function of the wavelength [μm] and absolute temperature of a black body

Solar radiation for building simulations may refer to the visible component, for checking daylight problems or may regard the whole spectrum of electromagnetic radiation, for considering heating and cooling problems.
When dealing with solar radiation and building models the complexity of phenomena which take place in the atmosphere has to be considered (Figure 4). Sunlight reaching the Earth's surface unmodified by any of the atmospheric processes is termed direct solar radiation. Solar radiation that reaches the Earth's surface after it was altered by the process of scattering is called diffused solar radiation. It is also called skylight, diffuse skylight, or sky radiation and is the reason for changes in the colour of the sky.
The percentage of the sky's radiation that is diffuse is much greater in higher latitude, cloudier places than in lower latitude, sunnier places. Also, the percentage of the total radiation that is diffuse radiation tends to be higher in the winter than the summer in these higher latitude, cloudier places. The sunniest places, by contrast, tend to have less seasonal variation in the ratio between diffuse and direct radiation.

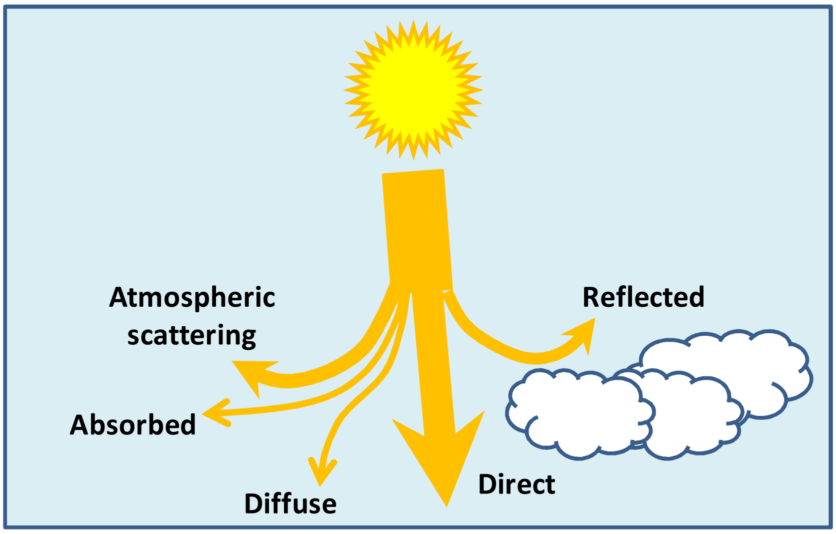


Figure 4: Phenomena involved in the solar radiation transmission through the atmosphere.

The amount of direct or diffuse solar radiation which reaches the ground depends on the latitude and altitude of the considered location, the pollution of the atmosphere, the day of the year, the considered hour and the actual weather conditions. All these aspects lead to variable conditions of solar radiation on the ground. For this reason for energy purposes it is important to build robust climatic data, in order to describe in the most proper way the average values of solar energy reaching the ground.
One important parameter is the concept of Air Mass (AM), which defines, in a mathematical way, the absorption of solar radiation as a function of the volume the radiation has to go through the atmosphere. The distance the solar radiation has to cover depends on the inclination angle of the solar height and an horizontal plane on the ground. Based on this definition (Figure 5):

- $AM = 0$ outside the atmosphere;
- $AM = 1$ is a ray perpendicular to the ground surface;
- $AM > 1$ is a ray passing through atmosphere in a direction which is not perpendicular to the ground surface.

When dealing with solar radiation, the real shape of the spectrum of specific energy has to be considered. Outside the atmosphere the average specific energy of solar radiation is equal to 1353 W/m^2, named solar constant (I_{sc}), which is defined as the mean specific energy over the year striking a plane normal to solar radiation direction. Considering the eccentricity of the

Earth's orbit, the normal solar radiation outside the atmosphere in the generic day d can be calculated as:

$$I_N = I_{sc}\left[1 + 0.033\cos\left(\frac{360 \cdot d}{365}\right)\right] \tag{5}$$

Depending on the AM value the solar radiation is absorbed by the different gases (mainly O_3, O_2, H_20, CO_2). As shown in Figure 6, the spectral irradiance outside the atmosphere and after an AM =1 path at sea level is shown. The shape of extraterrestrial spectral irradiance is similar to the one emitted by a black body surface.
Another important component of solar radiation is the reflected radiation, which describes sunlight that is reflected off of non-atmospheric things such as the ground. An important aspect to consider when dealing with building simulation is the effect of the snow which can sometimes raise the percentage of reflected radiation quite high. Fresh snow reflects 80 to 90% of the radiation striking it. As an example, some values of reflectivity ρ_g are listed in Table 4.

Table 4: Values of the reflection coefficient for different surfaces

Type of surface	**Reflection coefficient ρ_g**
Urban environment	0.14 ÷ 0.2
Grass	0.15 ÷ 0.25
Snow	0.82
Wet snow	0.55 ÷ 0.75
Asphalt	0.09 ÷ 0.15
Concrete	0.25 ÷ 0.35
Red tile	0.33
Aluminium	0.85
Copper	0.74
Steel	0.35
Steel with dirty surface	0.08

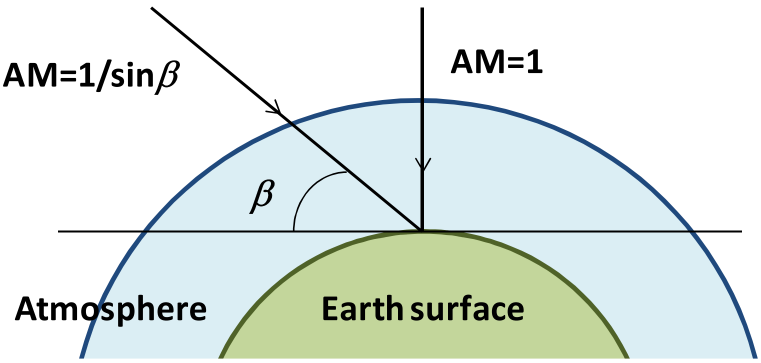


Figure 5: The concept of air mass.

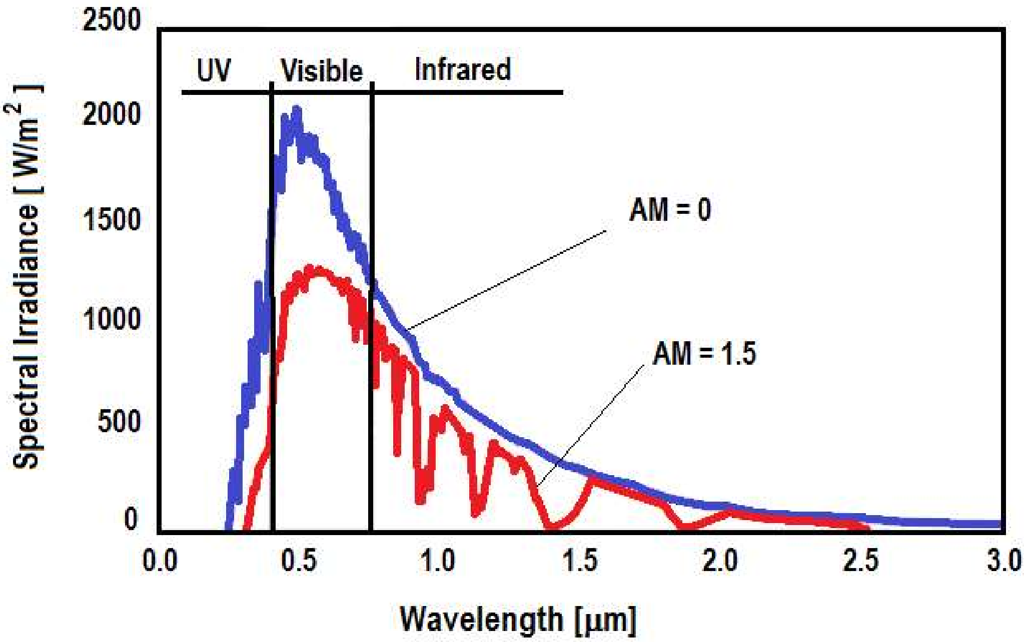


Figure 6: Spectral irradiance outside the atmosphere (AM=0) and after a path with AM=1.5 at sea level.

Interaction between solar radiation and buildings

In the analyses of energy in buildings the solar radiation has to be evaluated and particularly the energy coming onto the different opaque and glazed surfaces. Hence it is important to define the mutual position of the considered surface and the sun as well as the view factors between the surface and the sky and the surface and the ground.

For this purpose the following parameters have to be considered:

- Mutual position of the Sun and the location in the World (Figure 7):
    - Latitude of point P (ϕ): angle between the segment OP and the equatorial plane (positive in North direction, negative in South direction);
    - Longitude of point P (μ): angle, measured on the equatorial plane, between the projection of the segment OP and the Greenwich meridian (positive West direction, negative East direction);
    - Sun's declination (δ): angle between the direction Sun-Earth and the equatorial plane (positive in North direction, negative in South direction);
    - Hour angle of the Sun (ω):angle, measured on the equatorial plane, between the projection of the segment OP and the direction Sun-Earth (positive West direction, negative East direction).
- Mutual position of the Sun and the considered surface of the building (Figure 8):
    - Solar height (β): angle of the impinging direct solar radiation on the horizontal surface;
    - Solar azimuth (ψ_{solar}): angle, measured on the horizontal surface, between the vertical angle containing the Sun and the North-South line. As for the convention in defining the positive or negative angle of the solar position, usually it is defined according to Figure 9;
    - Surface azimuth ($\psi_{surface}$): angle measured on the horizontal surface between the normal direction of the surface and the South direction;

- Slope of the surface ($\chi_{surface}$): angle between the plane containing the surface and the horizontal plane.

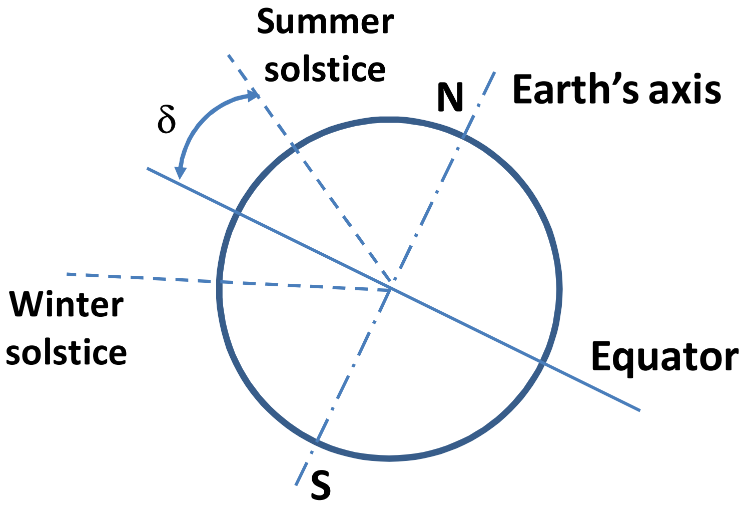


Figure 7: Parameters defining the mutual position between the Sun and the generic location on the Earth.

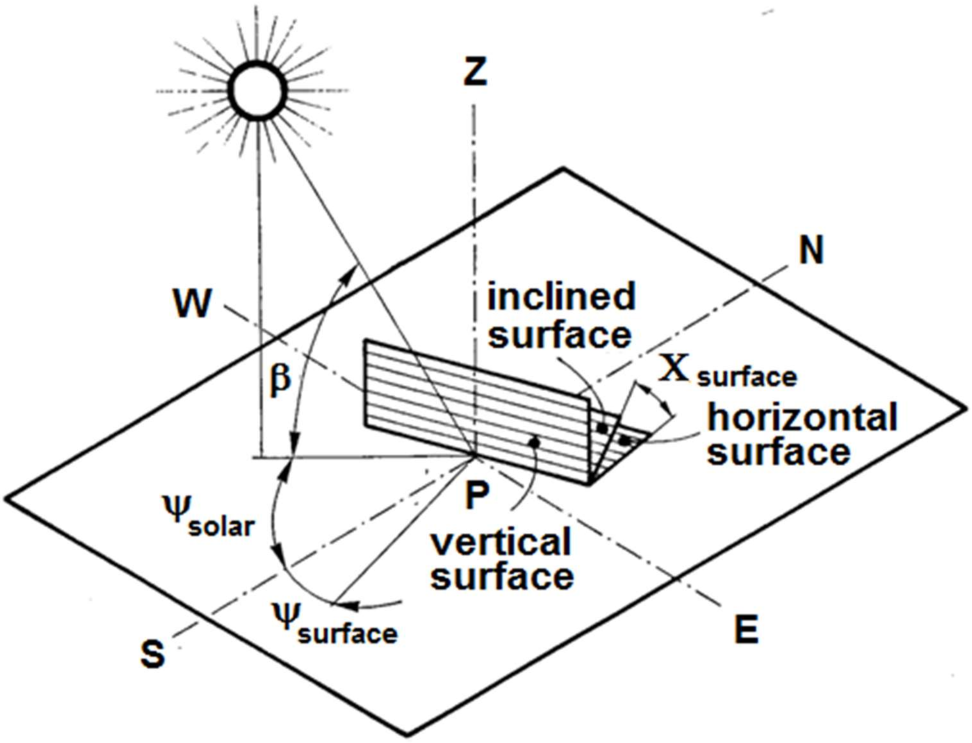


Figure 8: Parameters defining the mutual position between the Sun and the generic surface of the building.

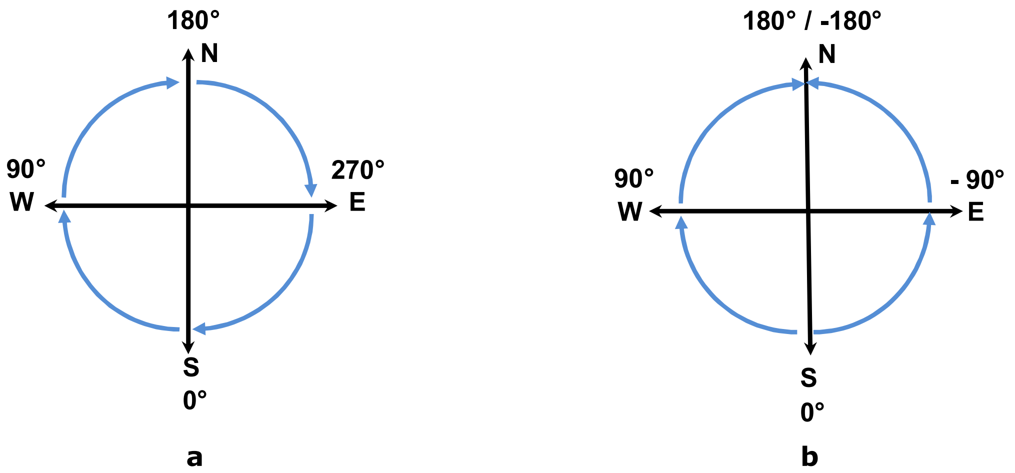


Figure 9: Usual definition of solar azimuth angle in a building simulation software.

At the end the solar radiation reaching the ground is the sum of the two components: direct solar radiation and diffuse solar radiation.
Named I_{DN} the normal direct solar radiation (the value of the solar radiation on a plane normal to the incident direct solar radiation, i.e. on a plane tilted with an angle $\chi_{surface}$ on the horizontal plane), the direct radiation I_b impinging a general surface can be calculated as:

$$I_b = I_{bN} \cos \vartheta \qquad (6)$$

where I_b=0 if cos $\vartheta \leq 0$.
Once determined the diffuse solar radiation striking the ground on an horizontal plane (I_{dH}), the amount of diffuse solar radiation which reaches the generic surface (I_d) can be calculated via the following equation:

$$I_d = I_{dH}(1 + \cos \chi_{surface}) / 2 \qquad (7)$$

This means that if the angle χ>0 the considered surface has a lower amount of solar radiation compared to an horizontal surface, due to the smaller view factor with the sky. At the same time the considered surface is struck by the solar radiation reflected by the ground (I_g), which can be calculated as follows:

$$I_g = \rho_g (I_d + I_{bN} sen\beta) \frac{(1 - \cos \chi_{surface})}{2} \qquad (8)$$

At the end, the overall solar radiation is the sum of the three components:

$$I_T = I_b + I_d + I_g \qquad (9)$$

The overall solar radiation can be calculated for a clear sky conditions or can be evaluated based on measured data.

Solar radiation in design conditions

As already described, design solar radiation in heating conditions is null. In cooling conditions, instead, the design solar radiation is based on clear sky conditions of the month which has the warmest temperature over the year. The solar radiation depends on the latitude of the considered place. As for the declination and the hour angle of the Sun, the following equations can be written:

$$\delta = 23.45 \cdot sen\left[\frac{360 \cdot (284 + d)}{365}\right] \tag{10}$$

$$\omega = 15(\tau - 12) + 0.25 \cdot [\Xi - 4 \cdot (\mu - \mu_0)] \tag{11}$$

where d is the considered day of the year, μ_0 is the longitude of the central meridian of the considered location [°], Ξ is the equation of time, i.e. the difference between apparent solar time and mean solar time, which can be interpolated from the values of Table 5 or can be calculated as [min]:

$$\begin{aligned}\Xi = {} & 0.42\cos(w) - 3.23\cos(2w) - 0.09\cos(3w) - 7.35 sen(w) - \\ & - 9.39 sen(2w) - 0.34 sen(3w)\end{aligned} \tag{12}$$

where $w = 2\,\pi\, d\,/\,365$.
For determining the normal direct solar radiation under clear sky conditions at the sea level, the following equation can be written [3]:

$$I_{bN} = \frac{A}{e^{\left(\frac{B}{sen\beta}\right)}} \tag{13}$$

where A is the extraterrestrial solar radiation if the rays were at the zenith and B is the atmospheric extinction (A and B are listed in Table 5).
In a similar way the diffuse solar radiation under clear sky conditions at the sea level can be calculated as:

$$I_d = CI_{DN}\frac{1 + \cos\chi_{surface}}{2} \tag{14}$$

where C is a diffuse solar radiation coefficient (Table 4).

Overall yearly solar energy radiation

The overall mean energy of the solar radiation which can be expected to impinge a plane during one year can be an important value to understand the available solar radiation energy.
Usually, when dealing with a unique value of the solar radiation representing the overall incoming energy, the available data refer to a horizontal plane. In order to determine the yearly solar radiation coming onto a plane with generic inclination, the dimensionless quantity Transposition Factor (*TF*) is defined as the ratio between the yearly incident solar energy over a differently oriented and inclined plane ($\overline{H}_y$) and the solar energy incident on the horizontal plane ($\overline{H}_{y,0}$):

$$TF = \frac{\overline{H}_y}{\overline{H}_{y,0}} \tag{15}$$

It describes the higher amount of energy which is possible to receive with a modules orientation and inclination different than respect to the horizontal position. As an example, in Figure 10 the transposition factor depending on the Azimuth angle and on the inclination of the considered surface.

Table 5: Parameters which allow to calculate solar radiation in the different months of the year (evaluated on the 21st day of the month)

	I_N [W/m^2]	e [min]	δ [°]	A [W/m^2]	B [-]	C [-]
January	1396	- 11.2	- 20.00	1230	0.142	0.058
February	1384	- 13.9	- 10.80	1214	0.144	0.060
March	1364	- 7.5	0.00	1185	0.156	0.071
April	1341	+ 1.1	+ 11.60	1135	0.180	0.097
May	1321	+ 3.3	+ 20.00	1103	0.196	0.121
June	1310	- 1.4	+ 23.45	1088	0.205	0.134
July	1311	- 6.2	+ 20.60	1085	0.207	0.136
August	1324	- 2.4	+ 12.30	1107	0.201	0.122
September	1345	+ 7.5	0.00	1151	0.177	0.092
October	1367	+ 15.4	- 10.50	1192	0.160	0.073
November	1388	+ 13.8	- 19.80	1220	0.149	0.063
December	1398	+ 1.6	- 23.45	1233	0.142	0.057

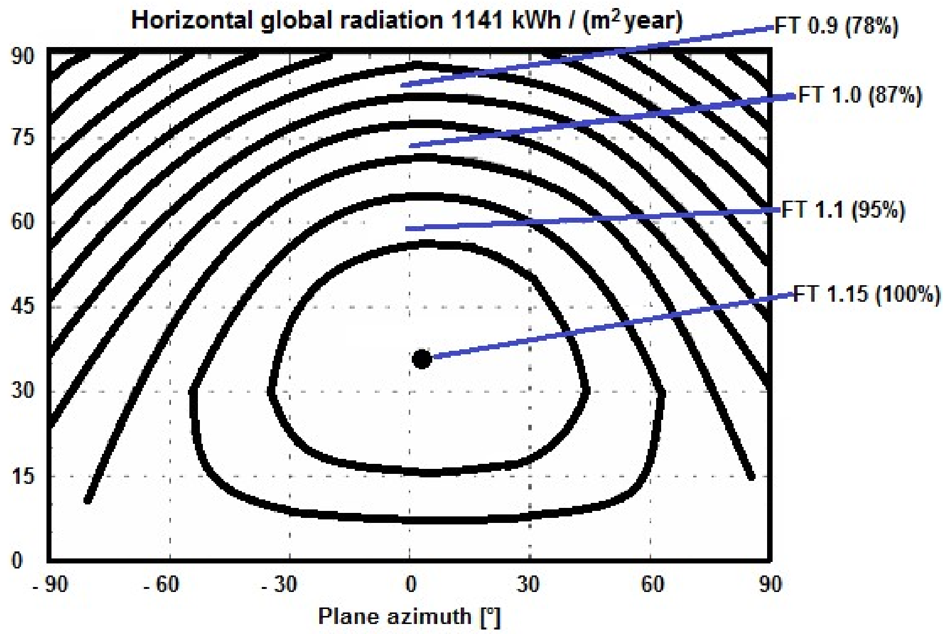


Figure 10: Example of Transposition Factor

Mean monthly solar energy radiation

Mean monthly solar energy radiation defines the mean radiation of each month of the year. For energy purposes this value may be sufficient to determine the net energy demand of a building by means of the so called quasi-steady state balance, based on an equation which solves the monthly balance of the building.

Usually data are available for the average value measured on an horizontal plane. Depending on details of the meteorological local apparatus the overall solar radiation or its direct and diffused components are available. In Table 6 the daily average total solar radiation on horizontal [kWh/m^2] for some locations is reported.

Table 6: Daily average total solar radiation on horizontal [kWh/m^2] for the locations of Table 3

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	4.22	5.32	5.55	6.51	7.64	7.77	7.40	7.22	6.62	5.71	4.56	3.94
2	2.07	2.82	4.01	5.14	6.22	7.48	7.53	6.63	5.42	3.52	2.14	1.81
3	6.80	5.58	4.67	3.38	2.31	1.93	2.06	2.72	4.04	4.83	5.84	6.38
4	4.71	5.18	5.87	5.59	5.05	5.09	4.79	4.34	4.61	4.40	4.70	4.59
5	2.33	3.05	4.23	5.30	6.01	6.03	5.27	4.87	4.76	3.44	2.36	2.06
6	0.53	1.18	1.93	3.84	4.84	5.04	5.11	4.35	2.74	1.54	0.80	0.41
7	6.84	6.08	4.90	3.60	2.59	2.08	2.29	3.05	4.21	5.29	6.52	6.79
8	2.98	4.01	5.31	6.39	7.39	7.32	6.89	6.24	5.60	4.51	3.37	2.80
9	7.98	7.20	5.74	4.10	3.04	2.37	2.49	3.52	4.69	6.12	7.51	7.85
10	5.02	5.56	5.94	5.54	5.35	5.85	5.51	6.16	5.88	5.09	4.67	4.36
11	1.76	2.49	3.44	4.39	5.98	6.29	6.18	5.16	4.19	2.94	1.82	1.50
12	4.78	5.45	6.53	6.54	6.66	6.13	5.60	5.29	5.41	5.40	4.68	4.45
13	0.99	1.89	2.88	4.22	5.49	6.04	6.14	5.34	3.67	2.25	1.19	0.80
14	0.25	0.91	1.87	3.58	5.31	5.74	5.44	4.02	2.35	1.12	0.31	0.12
15	2.83	3.28	4.27	4.92	5.44	5.95	6.18	5.47	5.06	4.25	3.19	2.61
16	5.71	5.42	5.85	5.13	3.91	2.78	2.78	2.86	3.30	4.22	4.46	5.08
17	0.71	1.19	2.12	3.64	4.91	4.91	5.02	4.35	2.97	1.75	0.97	0.55
18	6.94	6.11	4.90	3.33	2.17	1.62	1.94	2.77	4.08	5.33	6.54	6.45
19	4.13	4.74	5.43	5.70	5.63	5.63	5.52	5.65	5.10	4.66	4.01	3.52
20	1.66	2.88	4.42	4.56	5.75	6.34	6.01	5.20	4.16	2.57	1.47	1.27
21	0.48	1.20	2.33	3.49	5.04	5.44	5.16	4.12	2.39	1.33	0.58	0.35
22	4.52	5.31	6.20	6.86	6.56	4.84	3.77	3.84	4.20	5.11	4.74	4.27
23	6.04	6.56	5.81	4.89	4.34	4.07	4.01	4.74	5.34	5.20	4.72	5.35
24	3.25	3.68	5.39	6.96	6.61	6.79	5.93	5.10	4.84	4.28	3.92	3.26
25	1.65	2.60	3.68	4.47	5.53	5.99	5.78	5.95	4.17	3.59	2.04	1.50
26	0.78	1.39	2.28	3.63	4.61	5.31	5.36	4.86	3.12	2.03	1.04	0.61
27	3.29	4.16	5.34	7.09	7.84	8.32	7.62	7.13	6.34	4.82	3.77	3.07
28	4.28	5.06	5.77	6.41	7.34	8.03	7.82	7.43	6.89	5.99	4.71	3.60
29	1.89	2.92	3.98	5.39	6.32	7.60	7.28	6.37	5.33	3.69	2.30	1.56
30	5.65	5.39	4.86	4.27	3.34	3.13	3.33	4.15	4.63	5.06	5.58	5.85
31	2.53	3.39	4.44	5.49	6.70	7.19	7.56	6.89	5.32	3.97	2.83	2.30
32	6.60	5.63	4.87	3.74	2.66	2.18	2.56	3.56	4.58	5.64	5.99	6.38
34	4.55	4.99	4.80	4.97	4.68	4.47	4.63	4.51	4.57	4.48	4.23	4.12
35	0.26	0.76	1.77	3.74	5.28	5.36	5.06	3.81	2.32	1.18	0.45	0.20
36	0.78	1.43	2.75	3.83	4.63	5.40	5.47	4.89	3.30	1.70	0.93	0.66
37	3.06	4.17	5.51	6.48	7.95	8.74	7.99	7.83	6.81	4.98	3.96	2.81
38	2.52	3.15	3.54	4.61	4.79	4.14	4.39	4.81	3.47	2.93	2.49	2.09
39	0.80	1.57	2.65	4.55	5.61	5.97	6.56	5.31	3.92	1.79	0.94	0.64
40	1.03	1.67	2.97	3.93	4.64	5.39	6.05	4.93	3.21	2.00	1.25	0.76
41	2.02	2.75	3.88	5.09	5.63	6.46	5.98	5.26	4.30	3.45	2.22	1.83

Profile of hourly solar radiation of the month

The profiles of the hourly mean direct and diffuse radiation of the month can be used for determining the energy demand of buildings for both heating and cooling.

If the hourly values are not known the hourly trend of solar radiation can be built up by using the average monthly values of the solar radiation on horizontal surface. This is quite easy if the meteorological data are already divided into diffuse and direct radiation. If it is only available the overall daily energy on the horizontal, several procedures are available. One of the oldest methods is the Liu and Jordan approach [4]. It is based on on the cloudiness index, defined as the ratio between the monthly average solar radiation on the horizontal $\overline{H}_m$ and the monthly average solar radiation on the horizontal $\overline{H}_{m,0}$ in absence of atmosphere:

$$\overline{K}_h = \frac{\overline{H}_m}{\overline{H}_{m,0}} \tag{16}$$

The daily solar radiation on an horizontal surface can be calculated as:

$$H_0 = \frac{24}{\pi} I_N \left[\cos(\phi)\cos(\delta) sen(\omega_s) + \frac{\pi}{180}\omega_s \sin(\phi)\sin(\delta) \right] \tag{17}$$

where the angle corresponding to sun set ω_s [rad] can be calculated as:

$$\cos(\omega_s) = -tg(\phi) \cdot tg(\delta) \tag{18}$$

For determining the mean monthly solar energy, the following equation can be used:

$$\overline{H}_{m,0} = \frac{1}{d_2 - d_1} \sum_{d=d_1}^{d_2} (H_0)_d \tag{19}$$

where $(H_0)_d$ is the daily solar radiation on horizontal and d_1 and d_2 are respectively the first day and the last day of the considered month.

Usually $\overline{K}_h$ varies from 0 to 0.75. Since the fraction of diffuse radiation raises when cloudiness increases the relationship proposed by Liu and Jordan is the following one:

$$\frac{\overline{H}_d}{\overline{H}} = 1.390 - 4.027 \cdot \overline{K}_h + 5.531 \cdot \overline{K}_h^{\,2} - 3.108 \cdot \overline{K}_h^{\,3} \tag{20}$$

In case the only known value is number of sunny hours $\overline{n}$ and the average maximum theoretical number of hours of the day N, the following equations can be used for the diffuse and the beam solar radiation on horizontal:

$$\frac{\overline{H}_d}{\overline{H}_0} = 0.163 + 0.478 \cdot \left(\frac{\overline{n}}{N}\right) - 0.655 \cdot \left(\frac{\overline{n}}{N}\right)^2 \tag{21}$$

$$\frac{\overline{H}_b}{\overline{H}_0} = -0.176 + 1.450 \cdot \left(\frac{\overline{n}}{N}\right) - 1.120 \cdot \left(\frac{\overline{n}}{N}\right)^2 \tag{22}$$

where N [h] can be calculated as:

$$N = \frac{2 \cdot \omega_S}{15} \tag{23}$$

In Figure 11 the patterns of the hourly average values of solar radiation can be seen for three locations in Italy.

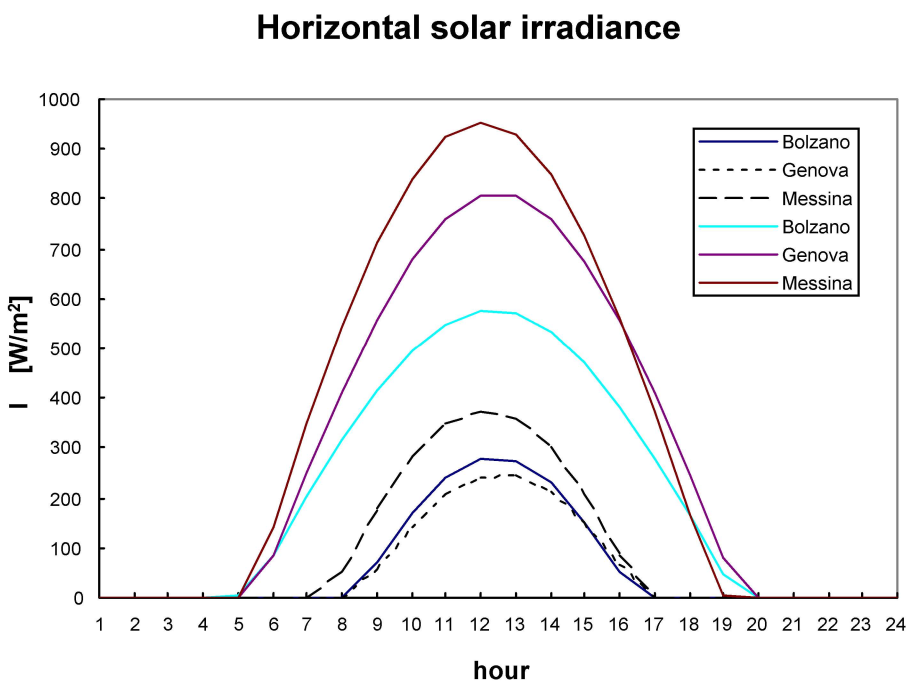


Figure 11: Average monthly solar radiation for Bolzano (North Italy, mountain area), Genua (North Italy, coast climate), Messina (South Italy, coast) for the coldest month (a) and the warmest month (b) of the year

Test Reference Year

The Test Reference Year (TRY) is the hourly average profile of solar radiation of one typical year, as described for the temperature hourly profile over the year. As already discussed, the most suitable trend of outdoor weather for determining the energy heating/cooling demands is based on real happened conditions. The use of artificial weather data may lead to mistakes, hence attention has to be paid on randomized generated data. As an example, in Figure 12 the trend of solar radiation over the year in Venice is shown.

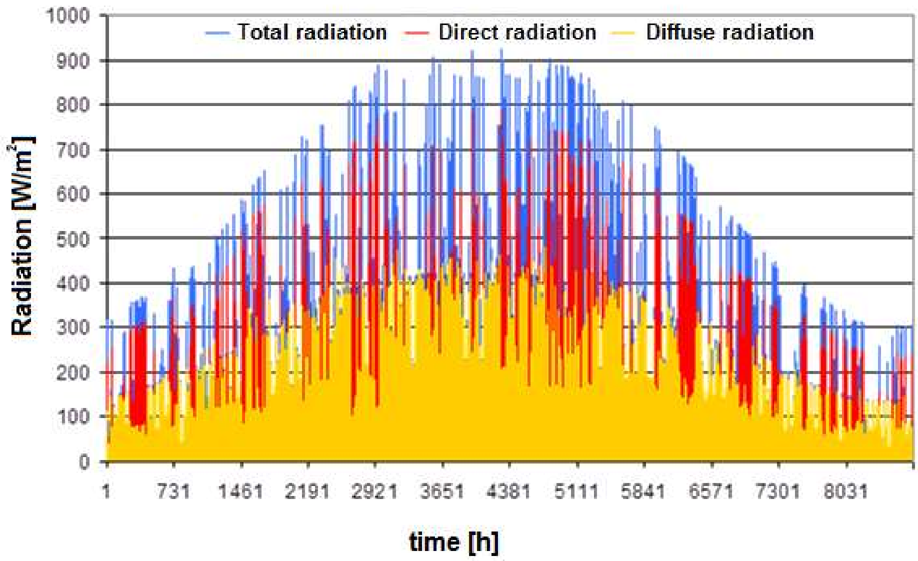


Figure 12: Example of solar radiation distribution over one year for the TRY of Venice

Effect of objects and landscape shadings

Building elements (e.g. roofs, overhangs, wings, etc.) may shade windows and walls (Figure 13). This aspect may affect the thermal balance of the building element and the one of the room. Depending on the considered time step (hourly calculation, daily value, monthly evaluation, seasonal analysis) the mean value of the shading area compared to the overall area over the considered time range has to be evaluated. This parameter is usually named shading coefficient f_{sh}.

Usually for the opaque wall the shading factor is considered explicitly, while for the windows the shading factor could be considered explicitly or it could be included in the solar factor or shading coefficient altogether with the energy characteristics of the glazing elements.

As already explained, the path of the sun across the sky changes with the time of year, as a function of the latitude. One typical diagram that is used to check the availability of solar radiation over the year is the so-called solar chart, which allows the calculation of the position of the sun in the sky at one point on the earth at a particular time of day. As an example, three possible solar charts are shown in Figure 14.A for 20° latitude, Figure 14.B for 40° latitude, Figure 14.C for 60° latitude. Usually the solar charts have to be coupled with a survey of possible obstacles, as shown in Figure 15. As well known the surroundings may affect the availability of solar radiation during a certain period of the year.

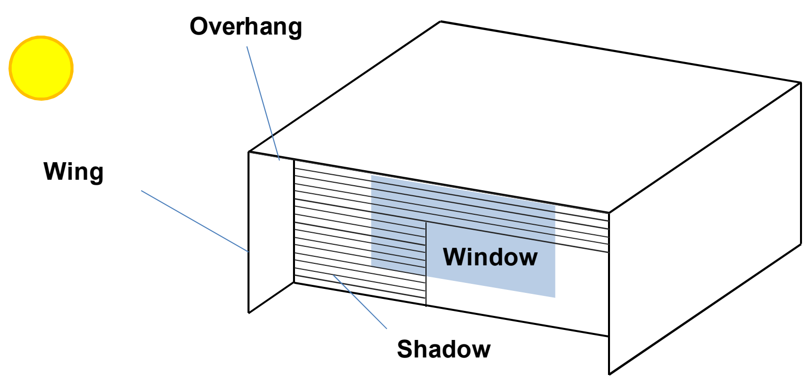


Figure 13: Example of architectural elements shading partially the building envelope

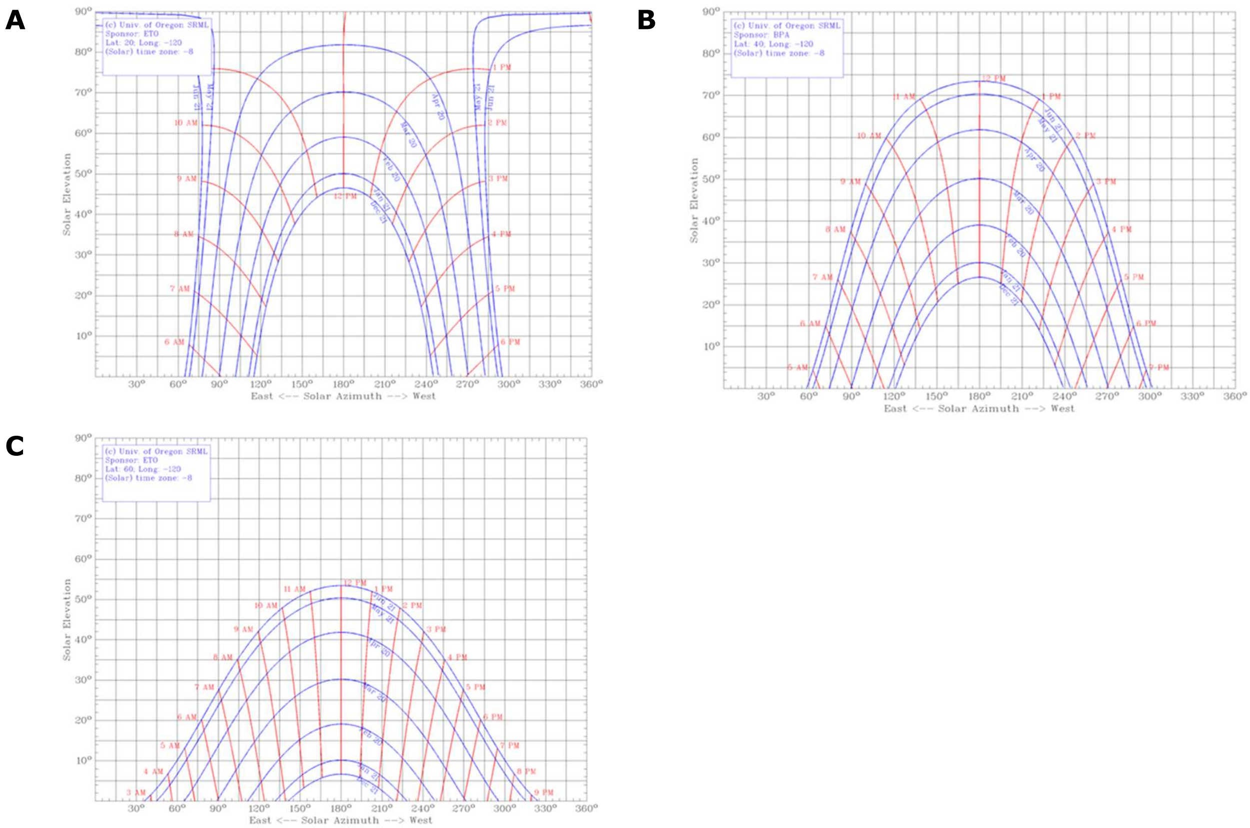


Figure 14: Solar charts for some locations: 20° latitude (A), 40° latitude (B), 60° latitude (C)

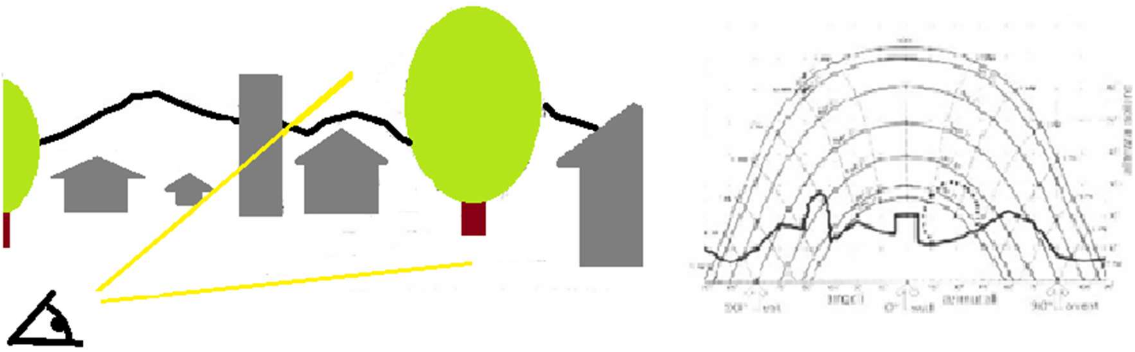


Figure 15: Solar chart and shape of surrounding area

Relative humidity and water vapour

The air can be supposed to be an ideal mixture of ideal gases: vapour and dry air (mixture of all the other gases). The specific humidity is the ratio between the mass of vapour and the mass of air:

$$\xi = \frac{m_v}{m_a} = \frac{\rho_v}{\rho_a} \tag{24}$$

Usually the specific humidity is expressed as grams of vapour per kilogram of air, since the absolute quantity of vapour is limited compared to the mass of air. Despite the small amount of

water in the mixture, the presence of the vapour is of big importance for the building physics (the envelope) and for the energy analyses (latent loads).
As for the energy related to the mixture air-vapour, the specific enthalpy [kJ/kg] of the air can be expressed as the combination of the specific enthalpy of the dry air h_a and the specific enthalpy of the vapour h_v via the following equation:

$$h = h_a + \xi \cdot h_v \tag{25}$$

where:

$$h_a = c_{pa} \cdot t \tag{26}$$

$$h_v = r_0 + c_{pv} \cdot t \tag{27}$$

Usually the humidity of the air is expressed in terms of relative humidity. It is defined as the ratio of the partial pressure of water vapour in the air-water mixture p_v to the saturated vapour pressure of water at those conditions p_{sat}:

$$RH = \frac{p_v}{p_{sat}} \tag{28}$$

The relative humidity of air depends not only on temperature but also on pressure of the system of interest. Relative humidity is often used instead of absolute humidity in situations where the rate of water evaporation is important, as it takes into account the variation in saturated vapour pressure.
Usually, when dealing with the air-vapour mixture, it may be useful to use the chart reported in Figure 16 for solving different problems.

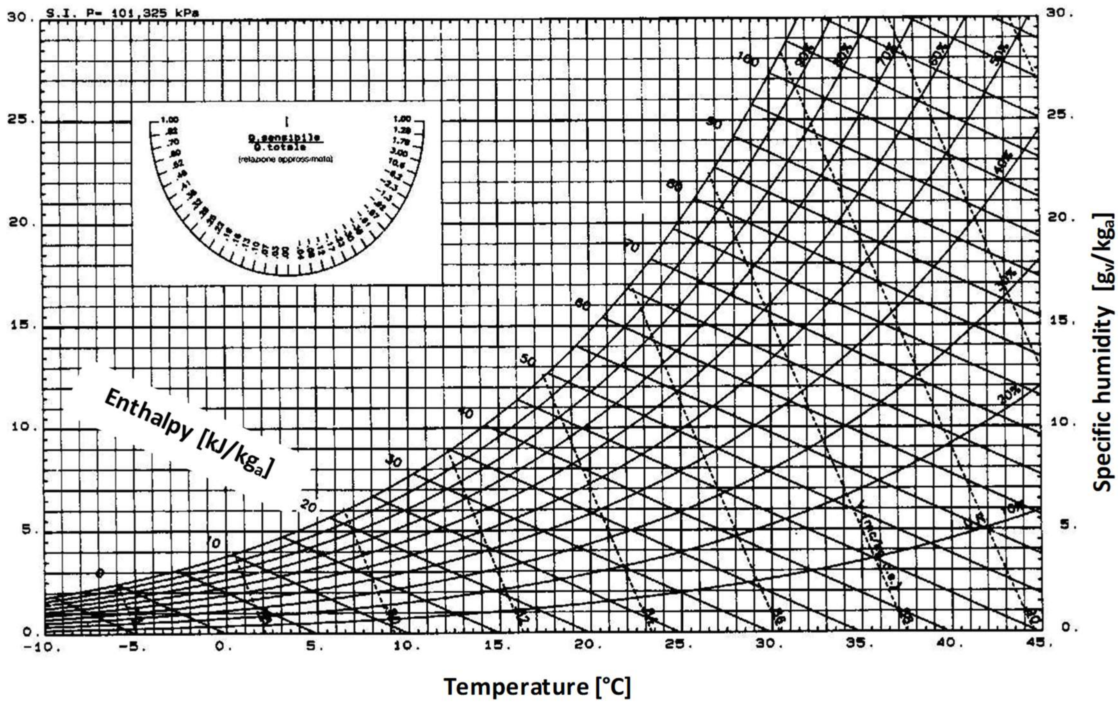


Figure 16: Diagram expressing relationship between air temperature and absolute humidity

The specific humidity ξ and the vapour pressure p_v are correlated by means of the equation:

$$\xi = 0.622 \frac{p_v}{p_{tot} - p_v} \tag{29}$$

where:

$$p_{tot} = p_a + p_v \tag{30}$$

If the saturation pressure p_{sat} is known, the correspondent temperature can be calculated as (valid for $p_{sat} \geq 610.5$ Pa and $p_{sat} < 610.5$ Pa respectively):

$$t = \frac{237.3 \log_e\left(\frac{p_{sat}}{610.5}\right)}{17.269 - \log_e\left(\frac{p_{sat}}{610.5}\right)} \tag{31}$$

$$t = \frac{265.5 \log_e\left(\frac{p_{sat}}{610.5}\right)}{21.875 - \log_e\left(\frac{p_{sat}}{610.5}\right)} \tag{32}$$

If the temperature is known, the correspondent saturation pressure p_{sat} can be calculated as (valid for $t \geq 0$°C and $t < 0$°C respectively):

$$p_{sat} = 610.5 \cdot e^{\frac{17.269 \cdot t}{273.3 + t}} \tag{33}$$

$$p_{sat} = 610.5 \cdot e^{\frac{21.875 \cdot t}{265.5 + t}} \tag{34}$$

Wind

Wind is the flow of gases on a large scale. On Earth, wind consists of the bulk movement of air. In meteorology, winds are often referred to according to their strength, and the direction from which the wind is blowing; wind direction is reported by the direction from which it originates. As for measurements, wind speeds are reported usually at a 10 m height and are averaged over a 10 minutes time frame.

The wind velocities of a meteorological station may be provided by means of measured values or by means of qualitative empirical values, e.g. by means of the Beaufort scale. Historically, the Beaufort wind force scale provides an empirical description of wind speed based on observed sea conditions. A description of the Beaufort scale can be seen in Table 7.

Wind has an impact on building energy since the velocity affects the convective heat exchange coefficients on the external surface of the envelope of a building. The most important effect, anyway, is the pressure that acts on the building due to the wind and the related infiltration rates, which increase if the wind is coupled with low temperatures of outdoor air. The effect of the pressure is also emphasized by the height of the building, since the wind velocity increases as a function of the height.

Usually, anyway, it is quite difficult to consider variable infiltration rates due to the wind velocity, since in this case the energy model has to be coupled with a model considering the air flow rates in a detailed way or via a resistance network. This aspect is not considered here in detail, but related papers can be found in literature, e.g. [5, 6, 7].

Table 7: Wind velocity expressed in the Beaufort scale

Beaufort strength	**Wind speed** [km/h]	[m/s]	**Qualitative description**
0	<1	<0.2	calm
1	1-5	0.3-1.5	light air
2	6-11	1.6-3.3	light breeze
3	12-19	3.4-5.4	gentle breeze
4	20-28	5.5-7.9	moderate breeze
5	29-38	8-10.7	fresh breeze
6	39-49	10.8-13.8	strong breeze
7	50-61	13.9-17.1	near gale
8	62-74	17.2-20.7	gale
9	75-88	20.8-24.4	strong gale
10	89-102	24.5-28.4	storm
11	103-117	28.5-32.6	violent storm
12	>118	>32.7	hurricane

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