# Chapter 1
# Fundamentals: Quantities, Definitions, and Units

**Jesús Polo, Luis Martín-Pomares, Christian A. Gueymard, José L. Balenzategui, Fernando Fabero and José P. Silva**

**Abstract** Solar radiation is a generic term that refers to different magnitudes of the solar electromagnetic radiation. The quantification of solar radiation incident at the Earth's surface is of high interest in many disciplines (radiative transfer in the atmosphere, meteorology and climatology, remote sensing of the atmosphere, solar energy studies, etc.). This multidisciplinary aspect of solar radiation sometimes produces duplication of names, definitions, or units. Moreover, different application-specific conventions for variable naming or units exist, which can be confusing. The solar irradiance that reaches a point at the Earth's surface is basically dominated by (i) the geometric aspects of the Earth's orbit around the Sun, and the inclination of its rotation axis in the ecliptic plane that determines the incident angle of the Sun rays; and (ii) the interaction mechanisms of solar radiation with various types of atmospheric constituents. This chapter intends to give the reader an overview of the basic definitions of the main variables that are commonly found in solar energy, and hence in this book as well. In addition, some basic aspects of solar geometry are briefly presented, followed by a concise description of

J. Polo (✉) · J. L. Balenzategui · F. Fabero · J. P. Silva
Photovoltaic Solar Energy Unit, Renewable Energy Division (Energy Department) of CIEMAT, Avda Complutense 40, 28040 Madrid, Spain
e-mail: jesus.polo@ciemat.es

J. L. Balenzategui
e-mail: jl.balenzategui@ciemat.es

F. Fabero
e-mail: fernando.fabero@ciemat.es

J. P. Silva
e-mail: josepedro.silva@ciemat.es

L. Martín-Pomares
Qatar Environment and Energy Research Institute, Hamad Bin Khalifa University, P.O. Box 5825, Doha, Qatar
e-mail: lpomares@hbku.edu.qa

C. A. Gueymard
Solar Consulting Services, P.O. Box 392, Colebrook, NH 03576, USA
e-mail: Chris@SolarConsultingServices.com



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the fundamentals of radiation-transfer modeling in the atmosphere. Detailed information on these topics, which is out of the scope of this book, can be found in many textbooks and the abundant literature on solar radiation, radiative transfer and atmospheric physics, to which the avid reader is referred for additional insight.

## 1 Basic Radiative Definitions

The Sun is a giant thermonuclear reactor: as a consequence of a chain of reactions of nuclear fusion type, helium is produced from hydrogen, releasing huge amounts of energy and charged particles into space. That influx of electromagnetic radiation is the primary source of energy on Earth. It is estimated that the Sun will continue emitting radiation in a *steady state* during about $5 \times 10^9$ more years. The electromagnetic radiation emitted by the Sun is distributed throughout space without interaction, following the inverse-square law. Therefore, the total power at the Sun's surface, $3.8 \times 10^{26}$ W, is reduced to $1.7 \times 10^{17}$ W at the mean Earth–Sun distance ($1.496 \times 10^{11}$ m), which defines the astronomical unit (AU). The spectral distribution of this radiation at the top of the Earth atmosphere (i.e., the variation of irradiance with wavelength $\lambda$ or frequency $v$) roughly fits that of a blackbody emitting at a temperature of ≈5770 K. Each solar photon hitting the Earth's surface first travelled ≈8 min through free interstellar space.

The solar constant is defined as the mean radiant flux of energy at 1 AU. That radiant flux, called total solar irradiance (TSI) varies somewhat as a consequence of varying solar activity over time, which is characterized by the 11-year Sun cycle. Since 1978, spaceborne radiometers have been measuring TSI with high precision. The solar constant is finally determined by the average value of TSI over many Sun cycles. Various solar constant values have been used in the solar literature, usually in the range 1365–1370 W m$^{-2}$ (Fröhlich and Brusa 1981; Iqbal 1983; Willson 1994). Recent measurements and analyses point out to a lower value, close to 1361 W m$^{-2}$ (Kopp and Lean 2011; Coddington et al. 2016). This was confirmed by a new revision of the main existing databases, which resulted in a reconstituted 42-year TSI time series and an average value of the solar constant of 1361.1 W m$^{-2}$ with an estimated standard uncertainty of 0.5 W m$^{-2}$ (Gueymard 2018a).

The rate of radiant energy received by a surface per unit area is called *irradiance*, whose unit is the Watt per square meter (W m$^{-2}$). When irradiance (an instantaneous quantity) is accumulated over time, it becomes *irradiation* (sometimes also referred to as "radiant exposure"). In principle, it should be expressed in the proper SI unit, i.e., kJ m$^{-2}$ or MJ m$^{-2}$. However, in most solar energy applications, the everyday kWh m$^{-2}$ unit is more frequently used, for convenience (1 kWh = 3.6 MJ). In many cases, hourly or sub-hourly irradiations are reported in terms of *average irradiance*, hence expressed in W m$^{-2}$. At time scales longer than one day or more, irradiations are normally reported in MJ m$^{-2}$ or kWh m$^{-2}$, but many climatological databases rather express irradiation in irradiance unit (W $m^{-2}$), which constitutes a source of confusion. What is implied here is that 1 W $m^{-2}$ is assumed constant over 24 h, and if integrated over the whole day would actually represent 24 Wh $m^{-2}$ or 86.4 kJ $m^{-2}$. For instance, the literature reports that, as a long-term average, the Earth receives ≈340 W $m^{-2}$ at the top of its atmosphere and ≈240 W $m^{-2}$ at the bottom. Note that the colloquial term *insolation* is vague and should be completely avoided since it is not a scientific term.

Generally speaking, the interaction between radiation and atmospheric constituents results in two basic types of attenuation: scattering and absorption. What is not either scattered or absorbed by the atmosphere is transmitted. (Note that what appears to be reflected by clouds is actually caused by scattering.) The transmitted solar radiation that reaches the surface is also partially reflected to space. The reflected fraction of the incident solar radiation is characterized by the *reflectance* (or *albedo*) of the surface. Similarly, the fraction absorbed is the *absorptance*, and finally, the fraction transmitted is called the *transmittance*. Globally, the sum of these three fractions must be equal to 1. Of that total, the long-term mean Earth albedo is ≈0.3. Ultimately, what is absorbed by the atmosphere and the surface is radiated back to space in the form of thermal (infrared) radiation.

In solar energy applications, the orientation and inclination of the receiver or collector (i.e., the observer's relative position) determine both the definition and the name of the incoming solar irradiance. Thus, the term *global horizontal irradiance* (GHI) refers to the total solar irradiance incident on a horizontal surface. Accordingly, the term *global tilted irradiance* (GTI) denotes the total solar irradiance that is captured by a surface tilted with respect to the horizontal plane. In the framework of photovoltaic (PV) solar systems, it is commonplace to rather find this component referred to as the *plane-of-array* (POA) irradiance.

In remote sensing and radiative transfer, the terms *intensity* and *radiance* are frequently used too. Intensity, expressed in W $sr^{-1}$, is defined as the power emitted by a point per solid angle. Radiance (expressed in W $m^{-2}$ $sr^{-1}$) is the intensity emitted per unit of the projected surface. Lambertian surfaces are reflectors for which the emitted radiance is the same in all directions. Most natural surfaces are actually non-Lambertian to varying degrees. The irradiance incident on a surface can be obtained as the spatial integration of the radiance that it receives from all directions, e.g., from the whole sky or parts of it, and from surface reflections.

## 2 Solar Geometry

In all solar radiation studies, a key first step consists in precisely determining the apparent position of the solar disk relative to the observer. Since this needs to be done at any moment and for any observer's location, a general and accurate method is required. Various solar position algorithms have been proposed in the literature. One of the latest is called SG2 (Blanc and Wald 2012). Calculating the solar geometry involves the knowledge of several angles in the ecliptic and equatorial planes, inclination of the receiving surface, the plane of the Sun's apparent path, celestial dynamics, and the trigonometric relationships between all angles. For a horizontal surface, the Sun's position is determined by its zenith angle, $Z$, and azimuth, $\gamma_{\mathrm{Sun}}$. In that case, the zenith angle is also the angle of incidence on the horizontal plane. Azimuths are normally measured clockwise from north, although some other conventions exist. Trigonometric functions exist between latitude, solar declination, and hour angle. Moreover, the solar constant must be corrected for the deterministic variation in Sun–Earth distance, related to the *eccentricity* of the planet's orbit. The necessary irradiance correction varies on a daily basis, within ±3.34% during the year. Basic expressions for all these processes can be found elsewhere (Iqbal 1983; Garg and Datta 1993).

For an arbitrarily oriented and inclined surface defined by its tilt, $\varphi$, and azimuth, $\gamma$, the direction vector of the rays coming from the solar disk are determined by the angle of incidence, $\theta_{\mathrm{in}}$, which is the angle between the Sun and the position of the observer's direction vector and the normal vector to the surface plane (Fig. 1). This angle of incidence can be estimated from the trigonometric relationship relating the Sun's azimuth and zenith angles to the surface's azimuth and tilt angles,

$$\cos\theta_{\mathrm{in}} = \sin Z \cos(\gamma_{\mathrm{Sun}} - \gamma) \sin\varphi + \cos\varphi \cos Z. \tag{1}$$

Apart from its geographical latitude, the amount of radiation received by a surface depends, first, on the date and time, and second, on the relative position

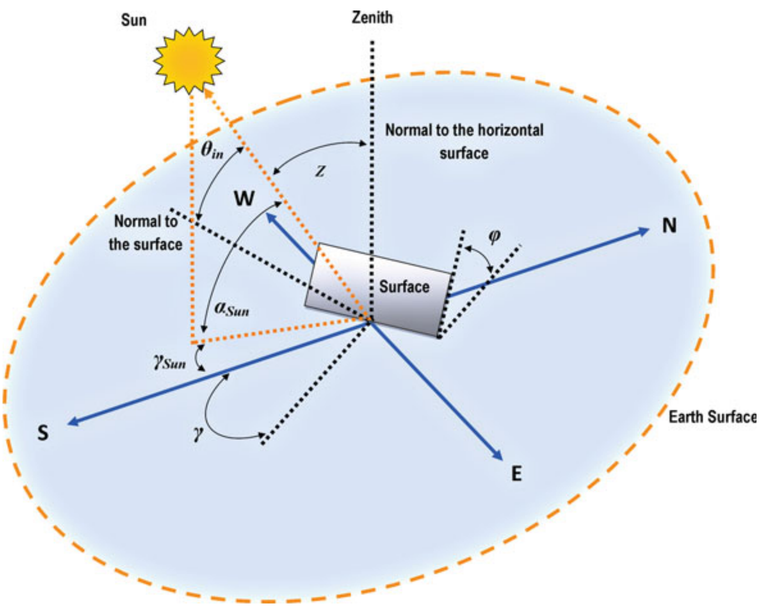


**Fig. 1** Basic solar geometry for the angle of incidence relative to an arbitrary oriented and tilted surface

between the Sun and the perpendicular to the plane (with orientation $\gamma$ and tilt $\varphi$). The direct irradiance is maximum at normal incidence ($\theta_{in} = 0$). Figure 2 shows an example of the variation of the Sun's position ($\gamma_{Sun}$, $Z$) along the year in the specific case of an observer located at Madrid, Spain. For any other direction or angle $\theta_{in}$ out from the normal to the surface, the direct irradiance is reduced as a function of $\cos(\theta_{in})$—the so-called Lambert's cosine law (McCluney 1994). Moreover, the optical reflectance $\rho(\lambda, \theta_{in})$ of the absorbing surface of detectors or collectors usually increases with incidence angle (Martin and Ruiz 2001; Balenzategui and Chenlo 2005).

Since the Sun's position is a strong function of time, it is important to define the temporal reference correctly. Measured and modeled databases report solar radiation data relative to a *timestamp,* which characterizes how the date and time information is related to the digital data. For an instantaneous value, the timestamp corresponds to that specific moment, or "snapshot," at which the event is recorded by a sensor, computer, or datalogger. In the case of irradiations, or irradiances averaged over short (hourly or sub-hourly) periods, such as one-min data in many observational databases, the timestamp may correspond to the start of the period (forward reference), to its end (backward), or (rarely) to its mid-time (middle reference). Moreover, the reported radiation quantities can have various meanings:

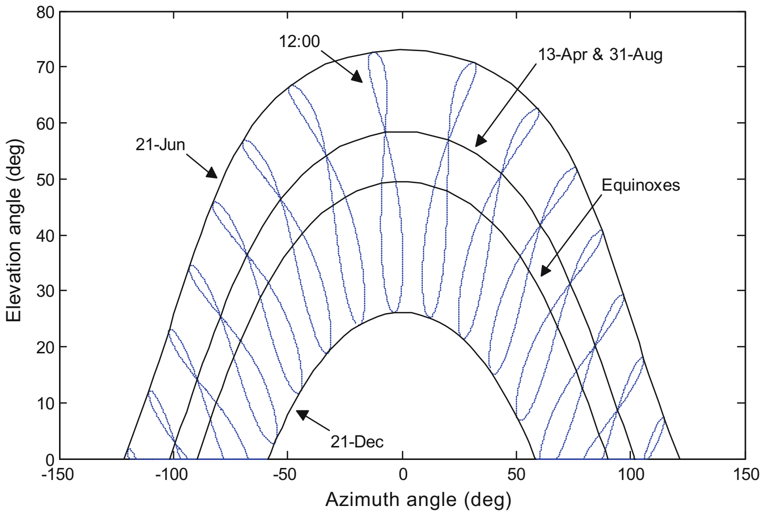


**Fig. 2** Sun's position along the year for Madrid, Spain (located 40.45°N, 3.73°W). The dotted curves represent the *analemma*, a diagram formed by the Sun's position at a fixed time of the day along the year. Each analemma in the figure differs one hour to the next (given in UTC). The pattern represented by the analemma is caused by a combined effect of the Sun's declination, the tilt of the Earth's axis, and the Earth's orbital eccentricity. The Sun's position coincides at a certain hour for only two days in the year (13-Apr and 31-Aug) in the Northern hemisphere

- *Instantaneous* values, usually for time steps of 1 s ("true irradiances"), expressed in terms of W $m^{-2}$;
- *Averaged* irradiance values, usually for sub-hourly to monthly periods (W $m^{-2}$);
- *Integrated* irradiation values for hourly, daily, monthly, or annual periods, expressed as kWh $m^{-2}$ or MJ $m^{-2}$ over the appropriate period.

The recording time reference is shown in Fig. 3 for three types of hourly records. For instance, a radiation quantity reported with a timestamp of 01:00 h could mean:

- A value referred to the time interval from 1:00 to 1:59 h (case A in the figure).
- A value referred to the time interval from 0:01 to 1:00 h (case B).
- A value assigned to the middle of the hour, hence 1:30 h would refer to the time interval from 1:00 to 2:00 h (case C).

This possible ambiguity of recording time reference is eliminated in instantaneous records, which are typical of spectral radiation measurements with spectroradiometers or sunphotometers, for instance.

Additionally, the timestamp may be referenced in terms of *local standard time* (LST), coordinated universal time (UTC), or local apparent time (LAT, also called solar time). Those three temporal references are related by

$$\mathrm{LST} = \mathrm{UTC} + \mathrm{TZ} = \mathrm{LAT} + \mathrm{TZ} - \mathrm{ET} - \mathrm{LL}/15 \tag{2}$$

where ET is the equation of time, TZ is the time zone (both expressed in hours), and LL is the local longitude (°). Both the latter and TZ are evaluated positively eastward of the Greenwich meridian and negatively westward. Note, however, that LST sometimes stands for local *solar* time, and that ET is sometimes defined with the opposite sign, which can create confusion. For years between 1900 and 2100, ET (in hours) can be approximated with

$$\mathrm{ET} = 0.16450\sin(2B) - 0.12783\sin(B + 78.7) \tag{3}$$

where $B = 360(N - 81)/365$, $N$ is the day number of the year (1–366), and all angles are in degrees.

In summary, the solar geometry affects the solar irradiance reaching the Earth's surface in two ways: (i) modification of the solar constant value due to the Sun–Earth astronomical distance, resulting in what is referred to as *extraterrestrial*

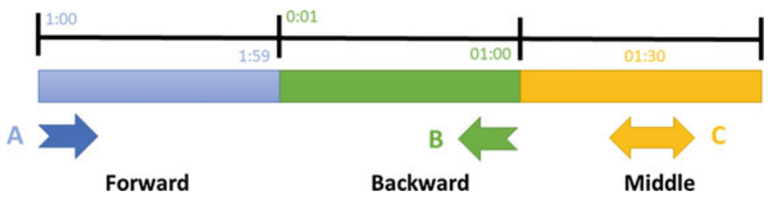


**Fig. 3** Recording time reference

*irradiance*; and (ii) actual apparent position of the Sun center relatively to the observer or receiver. The latter effect is the most important because it also conditions the atmospheric attenuation. The latter is discussed in the next section.

## 3 Components of Solar Radiation and Atmospheric Interactions

The combination of all the absorption and scattering processes that take place between solar photons and atmospheric constituents (air molecules, water vapor, ozone, carbon dioxide, aerosols, etc.) is referred to as atmospheric *extinction* or *attenuation*. Compared to the unattenuated irradiance at the top of the atmosphere (or extraterrestrial irradiance, as defined above), the amount of transmitted energy reaching the surface is highly variable, depending on conditions. Depending on geographical location, atmospheric conditions, and surface orientation, as much as ≈75–80% of the extraterrestrial irradiance can be received at the Earth's surface on an hourly average. The sky dome illuminates the receiver with diffuse irradiance, while the direct and circumsolar irradiances are received from the solar disk and its aureole, respectively. The fundamentals of these physical processes are briefly described next. For more precise and extended information, the reader may consult specific references dealing with atmospheric radiation and optics (Lenoble 1993; Thomas and Stamnes 1999; Liou 2002; Petty 2006).

Scattering is a physical process by which photons of electromagnetic radiation hit a particle that redirects the energy in all directions following a specific angular distribution. In the atmosphere, scattering particles range in size from air molecules ($\sim 10^{-4}$ μm) and aerosols ($\sim 1$ μm) to water droplets and ice crystals ($\sim 100$ μm). The angular distribution of the scattered intensity is closely related to the relative size of the scattering particle compared to the wavelength of the incident radiation. Assuming a spherical particle, it is common to define a *size parameter*, $a = 2\pi r/\lambda$, where $r$ is the radius of the particle. For very small values of the size parameter ($a \ll 1$), such as with air molecules, the process is called Rayleigh scattering. Its intensity is proportional to $\lambda^{-4}$, so that blue wavelengths are more intensely scattered than the red part of the spectrum, in turn creating the blue color of the sky.

For larger particle sizes, comparable to solar radiation wavelengths ($a \approx 1$), the process is called Mie scattering. This applies to the scattering caused by atmospheric aerosols. The angular distribution of the scattered intensity in Mie scattering is much larger in the forward direction and the wavelength dependence is weaker than in Rayleigh scattering. Finally, non-selective scattering occurs when the particles are much larger than the wavelength of radiation ($a \gg 1$). Non-selective scattering—a particular case of Mie scattering—is primarily caused by water droplets in the atmosphere. Its wavelength dependence is virtually non-existent, which makes fog and clouds appear white or gray.

The interaction of solar radiation with the atmosphere and the surface (land or water phases) produces the different components of the solar irradiance incident at the Earth's surface. In particular, the part of the incoming irradiance that is received by a plane normal to the direction of propagation and that comes directly from the solar disk without undergoing any attenuation is called direct normal irradiance (DNI). Its projection on the horizontal plane, more frequently used in atmospheric sciences, is called direct horizontal irradiance (DHI). Likewise, the solar irradiance component that is received from the whole sky as a result of the scattering process constitutes the diffuse irradiance. The global horizontal irradiance (GHI) is defined as the sum of DHI and the diffuse horizontal irradiance (DIF), such that

$$\mathrm{GHI} = \mathrm{DHI} + \mathrm{DIF} = \mathrm{DNI} \cos Z + \mathrm{DIF} \quad (4)$$

(Note that the solar component terminology can be confusing because some authors associate DHI with *diffuse* horizontal irradiance; additionally, the acronym DHI is sometimes replaced by BHI—beam horizontal irradiance—and, similarly, BNI is sometimes used as a replacement for DNI.) A part of GHI is reflected by the surface (more or less depending on its albedo) toward the sky. A fraction of this upward irradiance is scattered back to the surface, thus increasing GHI—a process called *backscattering*. This process is normally weak but can become intense in the case of a bright overcast sky over snow-covered ground. On a tilted surface, the global total irradiance (GTI) is defined as the sum of the direct, sky diffuse, and ground-reflected components incident on that surface.

The precise definition of DNI may be interpreted in different ways, depending on context. Consequently, slightly different meanings can be found in the literature, depending on whether the circumsolar irradiance emanating from the sun's aureole is accounted for or not, as reviewed by (Blanc et al. 2014). The circumsolar irradiance is the diffuse irradiance emanating from the sky region closely surrounding the solar disk, which is known as the solar aureole (Sengupta et al. 2017). The circumsolar irradiance is the result of Mie scattering in the forward direction of the Sun and thus depends on the amount and type of aerosols or thin clouds. It is, in essence, diffuse radiation that behaves like direct radiation.

The instruments used for measuring DNI, called pyrheliometers, have a field of view that includes the circumsolar irradiance, within $\approx 2.5°$ from the sun center. Thus, the strict definition referring to the photons that do not interact with the atmosphere is conceptually useful for atmospheric physics and radiative transfer but can be confusing for ground observations and for the manipulation of multiple sources of data. For solar energy systems, the most useful definition of DNI is the one that includes the circumsolar radiation since it is effectively measured by pyrheliometers, and can also be collected by planar solar systems (Blanc et al. 2014). When using concentrators with high concentration ratios and small opening angles ($<1°$), however, the measured DNI is slightly overestimated since a part of the circumsolar irradiance is not intercepted.

# 4 Spectral Solar Radiation and Conversion Applications

Atmospheric absorption is the process whereby an incoming photon is captured by a molecule or atom, thus producing an electronic, vibrational or rotational transition, and ultimately heat. Some gases in the atmosphere, like $CH_4$, CO, $CO_2$, $N_2$, $N_2O$, $NO_2$, $O_2$, $O_3$, or water vapor, absorb the incoming solar radiation more or less strongly in various wavebands, which creates recognizable patterns in the spectral irradiance distribution at the surface. Aerosols and clouds also absorb photons, but relatively much less than they scatter them. Overall, this absorption process is the main source of energy in the atmosphere and tends to increase its temperature in different layers.

The extinction of solar radiation passing through the atmosphere modifies the spectrum of the incoming solar radiation. Figure 4 shows the extraterrestrial solar spectrum (Gueymard 2018b) compared with direct normal spectral irradiance at sea level obtained with the SMARTS model (Gueymard 1995, 2001), assuming a zenith angle of 48.2°. The absorption processes are particularly intense in some wavebands (e.g., because of water vapor around 1400, 1850, and 2600 nm), resulting in the irradiance being partially or completely attenuated. Strong absorption due to ozone also exists in the UV, which protects biological organisms from excessive dangerous radiation.

Additionally, the available irradiance at the surface depends on the optical pathlength that sunlight has to cross through the atmosphere. This varies during the day as a consequence of Earth's rotation. The air mass, AM or $m$, is the

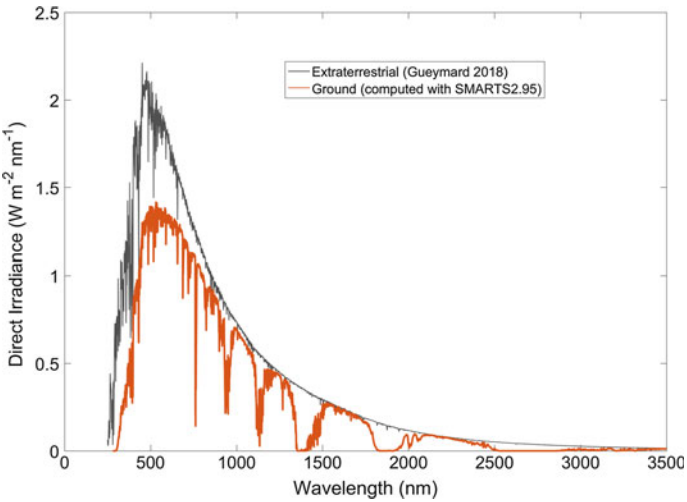


**Fig. 4** Spectral irradiance at sea level under typical atmospheric conditions and a zenith angle of 48.2°, compared to its extraterrestrial counterpart. Both quantities are evaluated at normal incidence

conventional variable used to estimate the ratio between the slant optical pathlength through the atmosphere, $L$, and its zenith (or vertical) counterpart, $L_0$, according to:

$$m = \frac{L}{L_0} \approx \frac{1}{\cos Z} \tag{5}$$

By definition, AM1 (or $m = 1$) is the air mass for a zenith sun. The simple expression in Eq. 5 is only an approximation, which starts to diverge at high zenith angles ($Z > 75°$). More elaborate expressions have been developed (e.g., Kasten and Young 1989; Young 1994), as further discussed in Chap. 5.

The air mass is an essential variable that conditions the magnitude of each broadband irradiance component, as well as the distribution and magnitude of its spectral counterpart. Conventionally, the spectral distribution outside the atmosphere is referred to as the AM0 spectrum (i.e., the spectrum for "zero atmosphere"). A common type of reference spectrum is used in solar applications such as photovoltaic or thermal systems, and is referred to as AM1.5 (corresponding to a zenith angle of 48.2°) because that air mass is representative of the mean annual sun's position at mid-latitudes. AM1.5 was historically selected as a reference for the development of standards such as ASTM G173 (ASTM 2012) or IEC 60904–3 (IEC 2016), in combination with specific atmospheric conditions derived from an analysis of solar irradiance data over the Southwestern USA (Gueymard et al. 2002). In these standards, the spectral distributions of both DNI and GTI are synthetically generated with the SMARTS code (Gueymard 1995, 2001).

From a broader spectral standpoint, solar radiation can be classified into three main wavebands:

- Ultraviolet (UV) radiation, for wavelengths below 400 nm (photons with energy larger than 3.1 eV). According to the International Electrotechnical Committee (IEC 1987), UV is further divided into three bands: UVA or A-type ($\lambda \in [315, 400]$ nm), UVB or B-type ($\lambda \in [280, 315]$ nm), and UVC or C-type ($\lambda \in [100, 280]$ nm). Fortunately, essentially all the dangerous UVC is absorbed in the stratosphere (mainly by ozone and oxygen). UVB is also strongly attenuated by ozone and is very low at the surface.
- Visible (VIS) radiation, for wavelengths between 400 and 760 nm (photon energy between 1.6 and 3.1 eV). This range corresponds to that of a typical human eye (the *photopic* range), though limits of sensitivity vary on an individual basis. Following the Commission Internationale de l'Éclairage (CIE 1987), the lower limit of the VIS range is sometimes taken between 360 and 400 nm, and the upper limit is sometimes extended up to 830 nm.
- Infrared (IR) radiation, for wavelengths larger than 760 nm (photon energy below 1.6 eV). The near-infrared (NIR) extends to ≈4 μm. Beyond that limit, solar radiation is extremely small at the surface. The extraterrestrial spectrum has only 0.8% of its total energy at wavelengths beyond 4 μm, and less than 0.06% beyond 10 μm.

The relative energetic importance of each of the wavebands just mentioned is compared in Table 1. As seen, ≈45–50% of the total irradiance is contained in either the VIS or NIR range.

Another general classification of importance here opposes solar radiation—also referred to as shortwave (SW) radiation—to terrestrial radiation—also referred to as longwave (LW), infrared, or thermal radiation. The Earth's radiation budget (ERB) analyzes the balance between the incoming radiation (SW) and the outgoing radiation (partly reflected SW, and partly emitted LW). The SW and LW wavebands overlap somewhat between 3 and 10 μm, and the limit between them is not clearly defined. The WMO–CIMO guide to meteorological instruments and methods of observation (CIMO 2017) limits SW radiation to the range 300–3000 nm and LW to the range 3–100 μm. Another common limit used in practice is 4 μm because the quartz window of pyrheliometers transmits radiation up to that wavelength. This is also why the standard spectra discussed above are defined up to that limit.

What Earth receives from the Sun in terms of electromagnetic radiation is perceived by humans in two ways: light and heat. Light commonly refers to the visible range of spectral irradiance, while heat is associated with any source of radiation producing a rise in the temperature of, e.g., a sensor or collector. This disambiguation can be directly applied to the field of energy conversion. Figure 5 shows different ways of harnessing solar energy. The plot's left side applies to the conversion of solar radiation into heat by thermal processes, whereas the right side describes the direct conversion of radiation into electricity through photonic processes.

Thermal systems can be divided into passive systems (without mechanical systems, such as in bioclimatic architecture, greenhouses, or thermosyphon hot water collectors) and active systems (if the produced heat energy is moved away forcibly). Without optical concentration, active solar collectors can just produce low temperatures, referred to as "low-grade" heat. With optical concentration, high temperatures can be achieved for industrial process heat (concentrated solar thermal systems, CST), or to produce electricity with turbines, as in thermal power plants

**Table 1** Relative content of irradiance in selected wavelength ranges for different solar radiation spectral distributions according to the ASTM G173 Standard for the global spectrum (AM1.5G) on a 37° tilt and the direct normal spectrum (AM1.5D), as well as the corresponding extraterrestrial spectrum used by SMARTS to obtain these spectra

| Waveband | Range (nm) | AM0 | AM1.5G | AM1.5D |
|---|---|---|---|---|
| UV | 280–400 | 7.6% | 4.6% | 3.4% |
| VIS | 400–760 | 45.2% | 50.1% | 48.7% |
| NIR | 760–4000 | 47.1% | 45.2% | 47.6% |
| | 280–4000 | | | |
| Integrated irradiance (W $m^{-2}$) | | 1347.9 | 1000.4 | 900.1 |

Percentage values refer to the total irradiance over the whole spectral range (280–4000 nm) in each spectral distribution. At the top of the atmosphere, the irradiance between 280 and 4000 nm represents ≈98.6% of the solar constant

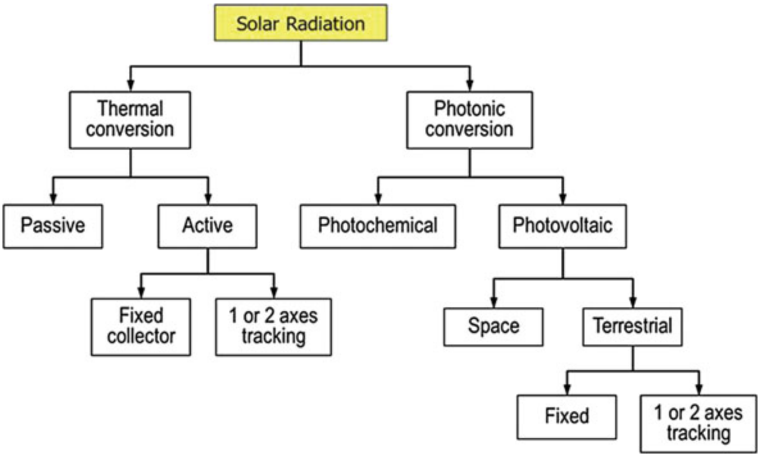


**Fig. 5** Different forms of conversion of solar radiation into usable energy

(concentrated solar power systems, CSP). Concentrators require 1-axis or 2-axis tracking. Flat-plate collectors can also be installed on 1-axis or 2-axis tracking systems to increase their resource potential.

In parallel, photonic systems (such as photovoltaic panels) take advantage of the quantum energy of photons. Their absorption in a semiconductor material promotes electronic excitations or transitions, which are used to produce an electrical current. Many semiconductor materials, technologies, and structural designs are developed to improve PV systems for both space and terrestrial applications. In the future, it can be expected that artificial photosynthetic systems will imitate natural plants. In that case, the spectral range of interest would be the photosynthetically active radiation (PAR), between 360 and 760 nm.

The broad range of conversion processes just reviewed provides some important keys to understand the importance of the correct evaluation of the solar resource, beyond the basic needs of energy conversion, meteorology, environment, or climate change.

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## References

ASTM (2012) Standard tables for reference solar spectral irradiances: direct normal and hemispherical on 37° tilted surface. Standard G173-03(2012). ASTM International. http://www.astm.org/Standards/G173.htm

Balenzategui JL, Chenlo F (2005) Measurement and analysis of angular response of bare and encapsulated silicon solar cells. Sol Energy Mater Sol Cells. https://doi.org/10.1016/j.solmat.2004.06.007

Blanc P, Wald L (2012) The SG2 algorithm for a fast and accurate computation of the position of the Sun for multi-decadal time period. Sol Energy 86:3072–3083. https://doi.org/10.1016/j.solener.2012.07.018

Blanc P, Espinar B, Geuder N et al (2014) Direct normal irradiance related definitions and applications: the circumsolar issue. Sol Energy 110:561–577. https://doi.org/10.1016/j.solener.2014.10.001

CIE (Commission Internationale de l'Éclairage) (1987) Methods of characterizing illuminance meters and luminance meters. CIE 69-1987. Vienna, Austria

CIMO (2017) Part I, Chapter 7 for solar radiation measurements. Part I, Chapter 16 for aerosols measurements. In: The CIMO guide. World Meteorological Organization. WMO guide to meteorological instruments and methods of observation (WMO-No. 8, 2014 edition, updated in 2017)

Coddington O, Lean JL, Pilewskie P et al (2016) A solar irradiance climate data record. Bull Am Meteorol Soc 97:1265–1282. https://doi.org/10.1175/BAMS-D-14-00265.1

Fröhlich C, Brusa RW (1981) Solar radiation and its variation in time. Sol Phys 74:209–215

Garg HP, Datta G (1993) Fundamentals and characteristics of solar radiation. Renew Energy 3:305–319. https://doi.org/10.1016/0960-1481(93)90098-2

Gueymard C (1995) SMARTS2: a simple model of the atmospheric radiative transfer of sunshine: algorithms and performance assessment. Rep. FSEC-PF-270-95. Florida Solar Energy Center, Cocoa, FL

Gueymard CA (2001) Parameterized transmittance model for direct beam and circumsolar spectral irradiance. Sol Energy 71:325–346. https://doi.org/10.1016/S0038-092X(01)00054-8

Gueymard CA (2018a) A reevaluation of the solar constant based on a 42-year total solar irradiance time series and a reconciliation of spaceborne observations. Sol Energy 168:2–9. https://doi.org/10.1016/j.solener.2018.04.001

Gueymard CA (2018b) Revised composite extraterrestrial spectrum based on recent solar irradiance observations. Sol Energy 169:434–440. https://doi.org/10.1016/j.solener.2018.04.067

Gueymard CA, Myers D, Emery K (2002) Proposed reference irradiance spectra for solar energy systems testing. Sol Energy 73:443–467. https://doi.org/10.1016/S0038-092X(03)00005-7

IEC (International Electrotechnical Commision) (1987) International electrotechnical vocabulary, Chapter 845: lighting. IEC 60050-845. Geneva, Switzerland

IEC (2016) Photovoltaic devices—Part 3: measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data. IEC 60904-3:2016 RLV Standard. International Electrotechnical Commission, Geneva, Switzerland

Iqbal M (1983) An introduction to solar radiation. Academic Press, Canada

Kasten F, Young AT (1989) Revised optical air mass tables and approximation formula. Appl Opt 28:4735–4738

Kopp G, Lean JL (2011) A new, lower value of total solar irradiance: evidence and climate significance. Geophys Res Lett 38:L01706. https://doi.org/10.1029/2010gl045777

Lenoble J (1993) Atmospheric radiative transfer. Deepak Publishing, Hampton

Liou K-N (2002) An introduction to atmospheric radiation. Academic Press, San Diego, USA

Martin N, Ruiz JM (2001) Calculation of the PV modules angular losses under field conditions by means of an analytical model. Sol Energy Mater Sol Cells 70:25–38. https://doi.org/10.1016/S0927-0248(00)00408-6

McCluney R (1994) Introduction to radiometry and photometry, 2nd edn. Artech House, Boston, London

Petty GW (2006) A first course in atmospheric radiation, 2nd edn. Sundog Publishing, Madison

Sengupta M, Habte A, Gueymard C et al (2017) Best practices handbook for the collection and use of solar resource data for solar energy applications. pp 1–233. https://doi.org/10.18777/ieashc-task46-2015-0001

Thomas GE, Stamnes K (1999) Radiative transfer in the atmosphere and ocean. Cambridge University Press, Cambridge

Willson RC (1994) Atlas of satellite observations related to global change. In: Turner JL, Foster CLP (eds) Weather. Wiley-Blackwell, Hoboken, pp 5–18

Young AT (1994) Air mass and refraction. Appl Opt 33:1108–1110. https://doi.org/10.1364/AO.33.001108