Chapter 2

Solar Radiation

2.1 GENERALITIES

Among the renewable resources, hydro is the predominant source used for electricity generation in several countries. The other significant growth in the renewable sector is solar energy, particularly if the cost of the construction of new solar power systems continues to decrease. In fact, experts predict that the price of producing solar power can be comparable to other sources of energy within the next 10 years.

Hermann [1] illustrates the availability of energy in the terrestrial environment. Most of the solar radiation reaching the terrestrial environment is dissipated and only a very small amount is converted into solar energy (959 PJ/year, while 1,356,048,000 PJ/year is dissipated only into surface heating).

International Energy Agency (IEA) [2] reports the worldwide solar conversion in 2011 of 711 PJ (74%) thermal, 234 PJ (24%) photovoltaic (PV), and 14 PJ (2%) concentrating solar power (CSP), in total 959 PJ/year (1 Peta-Joule = 10^{15} Joule). The potential of solar energy use is thus huge.

The absolute size of the solar electricity market is still very tiny, generating around 0.1% of electricity globally. Not surprisingly, there are significant differences between regions. As a result, electricity demand in non—*Organization for Economic Co-operation and Development* (non-OECD) countries will surpass the cumulative electricity demand in OECD countries before 2015. Over the past 20 years, solar electricity-generation technologies have grown by leaps and bounds, registering annual growth rates between 25% and 41%. Global solar electric generation technologies contribute roughly 2000 MW of electricity today.

In recent years, scientists have paid increasing attention to solar energy. There is a sudden demand in the utilization of solar energy for various applications such as water heating, building heating/cooling, cooking, power generation, and refrigeration [3].

Fig. 2.1 shows the distribution of the energy consumption in the residential sector of OECD member countries in 2011 [2]. The total yearly energy consumption of 25,000 PJ is a small fraction of the solar energy dissipated into surface heating. Space heating consumed almost 50% of the total (12,350 PJ) while space cooling consumed 6% (1610 PJ). The sector "services" that

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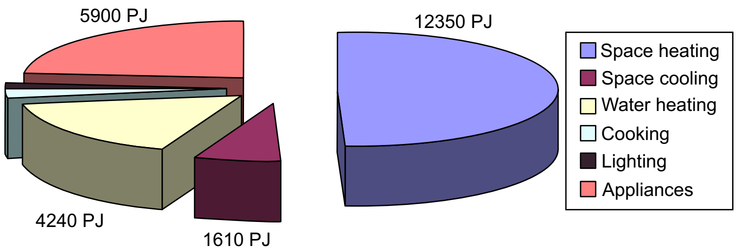

FIGURE 2.1 Energy use in the residential sector of OECD countries during 2011.

include utility buildings are not included in these numbers but also consume large amounts of energy for heating and cooling purposes (estimated around 7000 PJ). This indicates that about 10% of the energy use of OECD countries (225,752 PJ) has the potential to be served by solar-driven refrigeration/heat pump cycles. Although solar cooling is mainly considered for removing cooling loads from the applications, the same cycles used as heat pumps will also have an advantage in comparison to the direct use of solar heat for heating purposes.

Most countries are now accepting that solar energy has enormous potential because of its cleanliness, low price, and natural availability. For example, it is being used commercially in solar power plants. Sweden has been operating a solar power plant since 2001. In the Middle East, solar energy is used for desalination and absorption air-conditioning. In China and, to a lesser extent, Australasia, solar energy is widely used, particularly for water heating. In Europe, government incentives have fostered the use of PV and thermal systems for both domestic hot water and space heating/cooling. Romania's experience in solar energy represents a competitive advantage for the future development of this area, the country being a pioneer in this field. Between 1970 and 1980, around 800,000 m^2 of solar collectors were installed that placed the country third worldwide in the total surface of photovoltaic panels. The peak of solar installations was achieved between 1984 and 1985, but after 1990 unfavorable macroeconomic developments led to the abandonment of the production and investments in the solar energy field. Today about 10% of the former installed collector area is still in operation [4].

For solar energy use, its conversion into other forms of energy is needed. Solar technologies are broadly characterized as either passive solar or active solar depending on the way they capture, convert, and distribute solar energy. Passive solar techniques include orienting a building to the sun, selecting materials with favorable thermal mass or light dispersing properties, and designing spaces that naturally circulate air. Active solar technologies encompass solar thermal energy, using solar collectors for heating, and solar power by converting sunlight into electricity either directly using photovoltaic or indirectly using concentrated solar power.

Because of the many benefits that solar systems can provide, governments and the energy industry should be encouraged to find any new approach to develop a more cost-effective system. However, the majority of disadvantages about the solar power are more of economics in nature. Even after lots of technological development, the solar panels used to produce electricity are still quite expensive. A single solar panel can generate only a small amount of power. This means a larger number of solar panels are required to generate enough amount of electricity to power buildings and industries.

This chapter presents the main characteristics of solar energy and exposes a methodology for calculating and predicting solar radiation including the main computation elements and the estimation of solar radiation on tilted surface likely to be available as input to a solar device or crop at a specific location, orientation, and time.

2.2 CALCULATION OF SOLAR RADIATION

Before installing a solar energy system, it is necessary to predict both the demand and the likely solar energy available, together with their variability. Knowing this and the projected pattern of energy usage from the device, it is possible to calculate the size of collector and storage. Ideally, the data required to predict the solar input are several years of measurements of irradiance on the proposed collector plane. These are very rarely available, so the required (statistical) measures have to be estimated from meteorological data available (1) from the site, (2) (more likely) from some "nearby" site having similar irradiance, or (3) (most likely) from database.

2.2.1 Characteristics of Solar Radiation

The Sun is a sphere of intensely hot gaseous matter with a diameter of 1.39×10^9 m and is, on the average, 1.5×10^{11} m from the earth. As seen from the earth, the sun rotates on its axis about once in every 4 weeks. However, it does not rotate as a solid body; the equator takes about 27 days and the polar regions take about 30 days for each rotation. The sun has an effective blackbody temperature of 5777 K.

Solar energy is the result of electromagnetic radiation released from the sun by the thermonuclear reactions occurring inside its core. All of the energy resources on earth originate from the sun (directly or indirectly), except for nuclear, tidal, and geothermal energy.

The sun radiates considerable energy onto the earth. Solar radiation intensity, rarely over 950 W/m^2 has led to the creation of many types of devices to convert this energy into useful forms, mainly heat and electricity. Radiant light and heat from the sun is harnessed using a range of ever-evolving technologies such as solar heating, PV, CSP, solar architecture, and artificial photosynthesis.

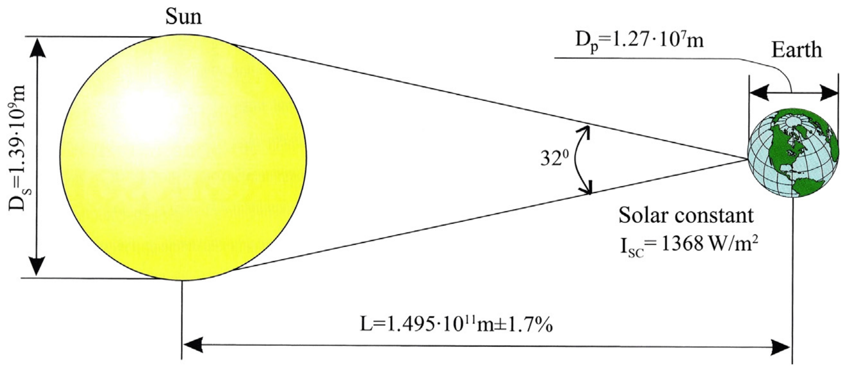

FIGURE 2.2 Geometry of the sun–earth system.

Fig. 2.2 shows schematically the geometry of the sun–earth relationships. The eccentricity of the earth's orbit is such that the distance between the sun and the earth varies by 1.7%. At a mean earth–sun distance $L = 1.495 \times 10^{11}$ m, the sun subtends an angle of 32 degree. The radiation emitted by the sun and its spatial relationship to the earth result in a nearly fixed intensity of solar radiation outside of the earth's atmosphere.

The *solar constant* I_{SC} signifies the energy from the sun per unit time received on a unit area of surface perpendicular to the direction of propagation of the radiation at mean earth–sun distance outside the atmosphere. The mean value of solar constant is equal to 1368 W/m^2. Therefore, considering a global plane area of 1.275×10^{14} m^2 and the mean radius of the earth being approximately 6371 km, the total solar radiation transmitted to the earth is 1.74×10^{17} W, whereas the overall energy consumption of the world is approximately 1.84×10^{13} W [5].

2.2.1.1 Solar Angles

The axis about which the earth rotates is tilted at an angle of 23.45 degrees to the plane of the earth's orbital plane and the sun's equator.

The earth's axis results in a day-by-day variation of the angle between the earth–sun line and the earth's equatorial plane called the solar declination δ. This angle may be estimated by the following equation [6]:

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + N)\right], \tag{2.1}$$

where $N =$ year day, with January 1 + 1.

The position of the sun can be defined in terms of its altitude β above the horizon and its azimuth ϕ measured in horizontal plane (Fig. 2.3).

To determine the angle of incidence θ between a direct solar beam and the normal to the surface, the surface azimuth ψ and the surface-solar

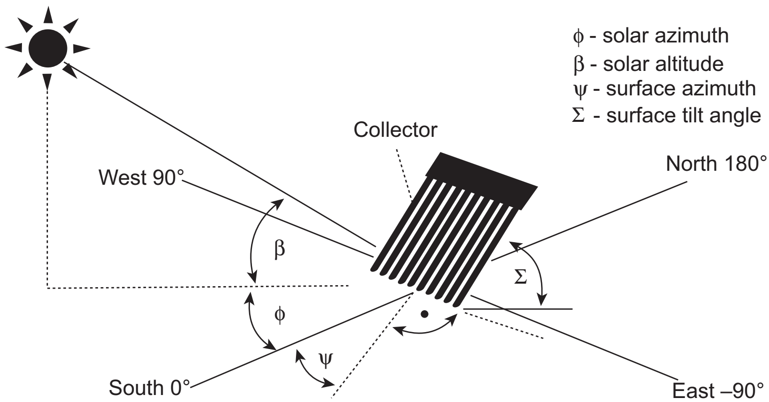

FIGURE 2.3 Solar angles with respect to a tilted surface.

azimuth γ must be known. The surface-solar azimuth is designated by γ and is the angular difference between the solar azimuth ϕ and the surface azimuth ψ. For a surface facing the east of south, $\gamma = \phi - \psi$ in the morning, and $\gamma = \phi + \psi$ in the afternoon. For surfaces facing the west of south, $\gamma = \phi + \psi$ in the morning and $\gamma = \phi - \psi$ in the afternoon. For south-facing surfaces, $\psi = 0$ degree, so $\gamma = \phi$ for all conditions. The angles δ, β, and ϕ are always positive.

For a surface with tilt angle Σ (measured from the horizontal), the angle of incidence θ is given by [6]

$$\cos\theta = \cos\beta \cos\gamma \sin\Sigma + \sin\beta \cos\Sigma. \tag{2.2}$$

For vertical surfaces, $\Sigma = 90$ degrees, $\cos\Sigma = 0$, and $\sin\Sigma = 1.0$, so Eq. (2.2) becomes

$$\cos\theta = \cos\beta \cos\gamma \tag{2.3}$$

For horizontal surfaces, $\Sigma = 0$ degree, $\sin\Sigma = 0$, and $\cos\Sigma = 1.0$, so Eq. (2.2) leads to

$$\theta = 90^\circ - \beta \tag{2.4}$$

Latitude φ is the angular location north or south of the equator, north positive; -90 degrees $\leq \varphi \leq 90$ degrees.

Zenith angle θ_Z, the angle between the vertical and the line to the sun, is the angle of incidence of direct (beam) radiation on a horizontal surface ($\theta_Z = \theta$).

Hour angle ω is the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15 degrees per hour;

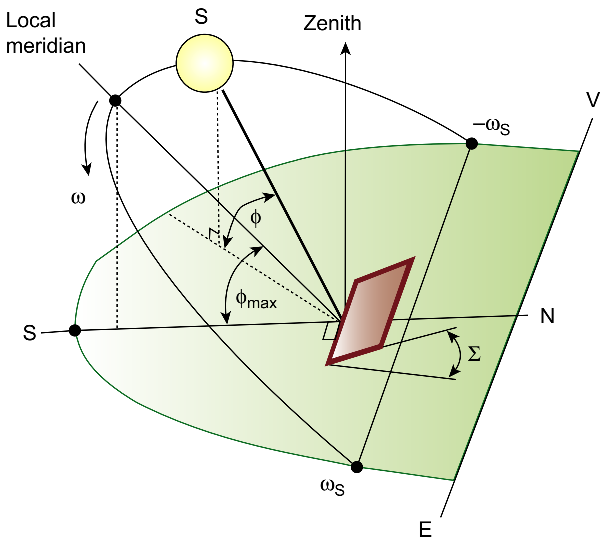

FIGURE 2.4 Hour angle ω.

morning negative ($-\omega_s$) and afternoon positive ($+\omega_s$) (Fig. 2.4). The sun position at any hour τ can be expressed as follows:

$$\omega = 15(12 - \tau) \tag{2.5}$$

If the angles δ, φ, and ω are known, then the sun position in the interest point can be easily determined for any hour and day using following expressions [7]:

$$\sin\beta = \sin\delta \sin\varphi + \cos\delta \cos\varphi \cos\omega = \cos\theta_z \tag{2.6}$$

$$\cos\phi = \frac{\sin\beta \sin\varphi - \sin\delta}{\cos\beta \cos\varphi}. \tag{2.7}$$

For any day of a year, solar declination δ can be determined in Eq. (2.1) and for the hour τ, hour angle ω can be calculated in Eq. (2.5). Latitude φ is also known and thus solar altitude β can be determined.

2.2.1.2 Design Value of Total Solar Radiation

Solar radiation reaches earth's surface as (1) direct (beam) solar radiation, (2) diffuse solar radiation, and (3) reflected radiation, which can be neglected. The total radiation received from the sun, of a horizontal surface at the level of the ground for a serene day, is the sum of the direct and diffuse radiations. Direct radiation depends on the orientation of receiving surface. Diffuse radiation can be considered the same, irrespective of the receiving surface orientation, although in reality there are small differences. Fig. 2.5 represents the proportion of the diffuse radiation in total radiation I_T [8].

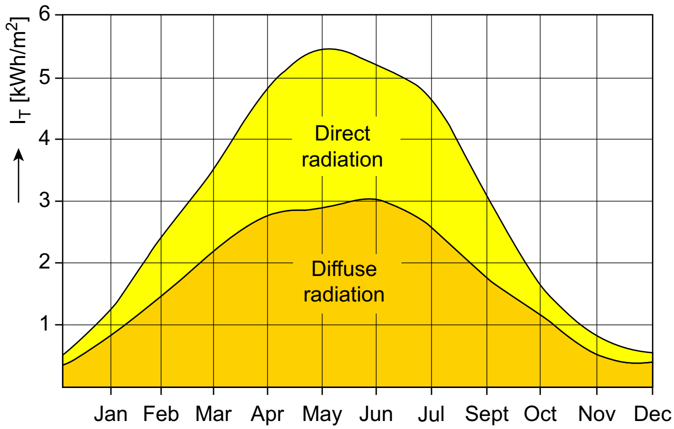

FIGURE 2.5 Total and diffuse solar radiation.

Attenuation of the solar rays is determined by the composition of the atmosphere and the length of the atmospheric path through which the rays travel. The path length is expressed in terms of the air mass m, which is the ratio of the mass of atmosphere in the actual earth–sun path to the mass that would exist if the sun was directly overhead at sea level ($m = 1$). Beyond the earth's atmosphere, $m = 0$. For zenith angles $\theta_z \in$ [0 degree, 70 degrees] at the sea level, to a close approximation, $m = 1/\cos\theta_z$.

The total solar radiation I_T of a terrestrial surface of any orientation and tilt with an incident angle θ is the sum of the direct component I_D plus the diffuse component I_d:

$$I_T = I_D + I_d \tag{2.8}$$

in which

$$I_D = I_{DN} \cos\theta \tag{2.9}$$

$$I_{DN} = A_0 e^{-B/\sin\beta}, \tag{2.10}$$

where I_{DN} is the direct normal radiation estimated by Stephenson [9] using Eq. (2.10); A_0 is the apparent extraterrestrial radiation at the air mass $m = 0$; B is the atmospheric extinction coefficient; β is the sun's altitude above horizon, in degrees [9].

Irradiance, expressed in W/m^2, is the rate at which radiant energy is incident on a surface per unit area of surface. *Irradiation*, expressed in J/m^2 or kWh/m^2, is the incident energy per unit area on a surface, found by integration of irradiance over a specified time, usually an hour or a day. *Insolation* is a term applying specifically to solar energy irradiation.

A simpler method for estimating clear-sky radiation by hours is to use data for the American Society of Heating, Refrigerating, and Air-Conditioning

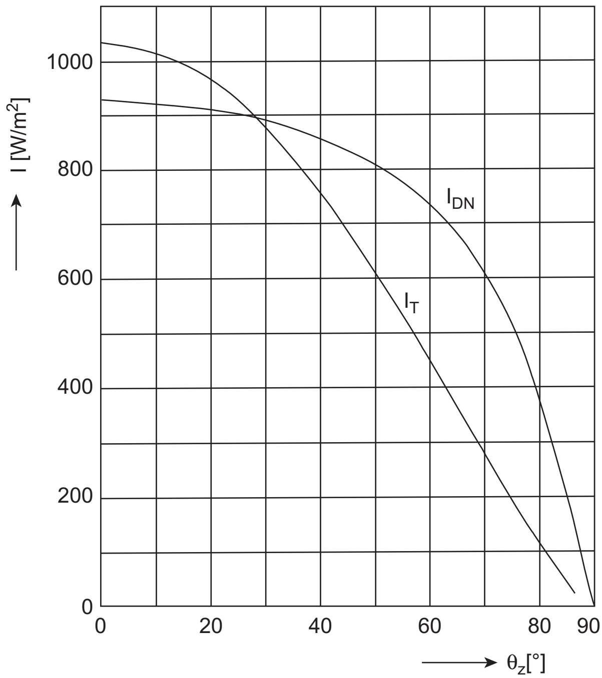

FIGURE 2.6 Total horizontal radiation and direct normal radiation for the ASHRAE standard atmosphere.

Engineers (ASHRAE) standard atmosphere. Farber and Morrison [10] provide tables of direct normal radiation and total radiation on a horizontal surface as a function of zenith angle θ_z. These are plotted in Fig. 2.6. For a given day, hour-by-hour estimates of radiation I (W/m^2) can be made based on midpoints of the hours.

The most common measurements of solar radiation are total radiation on a horizontal surface. The commonest instruments used for measuring solar radiation are of two basic types: a *pyroheliometer*, which measures the direct radiation I_D, and a pyranometer or *solarimeter*, which measures total radiation I_T.

Only the active cavity radiometer (ACR) gives an absolute reading. In this instrument, the solar beam falls on an absorbing surface of area A, whose temperature increase is measured and compared with the temperature increase in an identical (shaded) absorber heated electrically. In principle, then

$$\alpha A I_D = P_{el}. \tag{2.11}$$

The geometry of the ACR is designed so that, effectively, $\alpha = 0.999$ [11].

Unitary thermal energy received from the sun, measured at the level of earth's surface, perpendicularly on the direction of solar rays, for the conditions where the sky is perfectly clear and without pollution, in the areas of Western, Central, and Eastern Europe, around noon, can provide maximum 1000 W/m^2. This value represents the sum between direct and diffuse radiations. Atmosphere modifies the intensity, spectral distribution, and spatial distribution of the solar radiation by two mechanisms: absorption and diffusion. The absorbed radiation is generally transformed into heat, while the diffuse radiation is resent in all the directions into the atmosphere.

Meteorological factors that have a big influence on the solar radiation at the earth's surface are atmosphere transparency, nebulosity, and clouds' nature and their position.

Romania disposes an important potential of solar energy due to the favorable geographical position and climatic conditions. On 1 m^2 plate of horizontal surface, perpendicular on the incidence direction of the sun's rays, energy of 900 to 1450 kWh/year can be received, depending on the season, altitude, and geographical position. The daily mean solar radiation can be up to five times more intense in the summer than in the winter. There are situations when, in the winter, under favorable conditions (clear sky, low altitude, etc.), values of solar energy received can reach approx. 4−5 kWh/(m^2·day), the solar radiation being practically independent of the environment air temperature. Quantifying this value related to Romania's annual energy requirement situated around the value of 260,900,000 MWh, around the year 2011, energy of approx. 285,000,000,000 MWh/year radiated by the sun in the country's territory is obtained. This represents Romania's total energy consumption for a period of 1092 years!

2.2.2 Solar Radiation on a Tilted Surface

For purposes of solar process design and performance calculations, it is often necessary to calculate the hourly radiation on a tilted surface of a collector from measurements or estimates of solar radiation on a horizontal surface. The most commonly available data are total radiation for hours or days on the horizontal surface, whereas the need is for direct and diffuse radiation on the plane of a collector.

Fig. 2.7 indicates the angle of incidence of direct radiation on the horizontal and tilted surfaces. The geometric factor R_D, the ratio of direct radiation on the tilted surface to that on a horizontal surface at any time, of $I_{D,\Sigma}/I_D$ is given by:

$$R_D = \frac{I_{D,\Sigma}}{I_D} = \frac{I_{DN}\ \cos\theta}{I_{DN}\ \cos\theta_z} = \frac{\cos\theta}{\cos\theta_z}, \tag{2.12}$$

where $\cos\theta$ and $\cos\theta_z$ are both determined from Eq. (2.2).

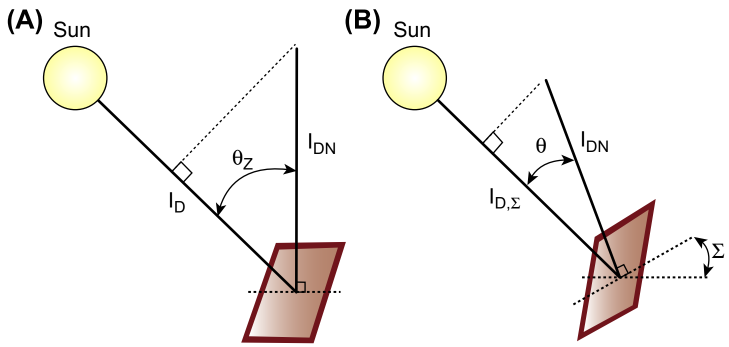

FIGURE 2.7 Direct radiation on horizontal and tilted surfaces.

Equations relating the angle of incidence θ of direct radiation on a surface to the other angles [12]:

$$\begin{aligned}\cos\theta &= \sin\delta\sin\varphi\cos\Sigma - \sin\delta\cos\varphi\sin\Sigma\cos\psi\\&+ \cos\delta\cos\varphi\cos\Sigma\cos\omega + \cos\delta\sin\varphi\sin\Sigma\cos\psi\cos\omega\\&+ \cos\delta\sin\Sigma\sin\psi\sin\omega\end{aligned} \tag{2.13}$$

and

$$\cos\theta = \cos\theta_z\ \cos\Sigma + \sin\theta_z\ \sin\Sigma\ \cos(\phi - \psi). \tag{2.14}$$

There are several commonly occurring cases for which Eq. (2.13) is simplified. For fixed surfaces sloped toward the south or north, with a surface azimuth angle ψ of 0 or 180 degrees (a very common situation for fixed flat-plate collectors), the last term drops out.

For vertical surfaces, $\Sigma = 90$ degrees, the equation becomes

$$\cos\theta = -\sin\delta\cos\varphi\cos\psi + \cos\delta\sin\varphi\cos\psi\cos\omega + \cos\delta\sin\psi\sin\omega. \tag{2.15}$$

For horizontal surfaces, the angle of incidence is the zenith angle of the sun, θ_z. Its value must be between 0 degree and 90 degrees when the sun is above the horizon. For this situation $\Sigma = 0$ degree and Eq. (2.13) becomes

$$\cos\theta_z = \cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta. \tag{2.16}$$

Useful relationships for the angle of incidence of surfaces sloped due north or due south can be derived from the fact that surfaces with slope Σ to the north or south have the same angular relationship to beam radiation as a horizontal surface at an artificial latitude of $\varphi - \Sigma$. Modifying Eq. (2.16) yields

$$\cos\theta = \cos(\varphi - \Sigma)\ \cos\delta\cos\omega + \sin(\varphi - \Sigma)\sin\delta. \tag{2.17}$$

For the special case of solar noon, for the south-facing sloped surface in the northern hemisphere,

$$\theta_{noon} = |\varphi - \delta - \Sigma| \tag{2.18}$$

and in the southern hemisphere,

$$\theta_{noon} = |-\varphi + \delta - \Sigma|, \tag{2.19}$$

where $\Sigma = 0$ degree, the angle of incidence is the zenith angle, which for the northern hemisphere is

$$\theta_{z,noon} = |\varphi - \delta| \tag{2.20}$$

and for the southern hemisphere,

$$\theta_{z,noon} = |-\varphi + \delta|. \tag{2.21}$$

For a plane rotated about a horizontal east–west axis with continuous adjustment to minimize the angle of incidence,

$$\cos\theta = \left(1 - \cos^2\delta \ \sin^2\omega\right)^{1/2}. \tag{2.22}$$

The optimum azimuth angle for flat-plate collectors is usually 0 degree in the northern hemisphere (or 180 degrees in the southern hemisphere). Thus, it is a common situation that $\psi = 0$ degree (or 180 degrees). In this case, Eqs. (2.16) and (2.17) can be used to determine $\cos\theta_z$ and $\cos\theta$, respectively, leading in the northern hemisphere, for $\psi = 0$ degree, to

$$R_D = \frac{\cos(\varphi - \Sigma)\ \cos\delta\ \cos\omega + \sin(\varphi - \Sigma)\ \sin\delta}{\cos\varphi\ \cos\delta\ \cos\omega + \sin\varphi\ \sin\delta} \tag{2.23}$$

In the southern hemisphere, $\psi = 180$ degrees and the equation is

$$R_D = \frac{\cos(\varphi + \Sigma)\ \cos\delta\ \cos\omega + \sin(\varphi + \Sigma)\ \sin\delta}{\cos\varphi\ \cos\delta\ \cos\omega + \sin\varphi\ \sin\delta}. \tag{2.24}$$

Eq. (2.13) can also be applied to other-than fixed flat-plate collectors. For example, for a plane rotated continuously about a horizontal east–west axis to maximize the direct radiation on the plane, from Eq. (2.22), the ratio of direct radiation on the plane to that on a horizontal surface at any time is

$$R_D = \frac{\left(1 - \cos^2\delta\ \sin^2\omega\right)^{1/2}}{\cos\varphi\ \cos\delta\ \cos\omega + \sin\varphi\ \sin\delta}. \tag{2.25}$$

Eqs. (2.23)–(2.25) are used to determine optimum tilt angle Σ for duration of 1 h or 1 day. For use in solar process design procedures, also it needs the monthly average daily radiation on the tilted surface. Thus, for surfaces that are sloped toward the equator in the northern hemisphere, that is, for surfaces with $\psi = 0$ degree,

$$\overline{R}_{\mathrm{D}} = \frac{\cos(\varphi - \Sigma)\ \cos\delta\ \sin\omega_s' + (\pi/180)\omega_s'\ \sin(\varphi - \Sigma)}{\cos\varphi\ \cos\delta\ \sin\omega_s + (\pi/180)\omega_s\ \sin\varphi\ \sin\delta} \tag{2.26}$$

in which ω_s' is the sunset hour angle for the tilted surface for the mean day of the month, which is given by,

$$\omega_s' = \min\begin{bmatrix} \cos^{-1}(-\tan\varphi\ \tan\delta) \\ \cos^{-1}(-\tan(\varphi - \Sigma)\ \tan\delta) \end{bmatrix} \tag{2.27}$$

and

$$\omega_s = \cos^{-1}(\tan\varphi\ \tan\delta), \tag{2.28}$$

where "min" means the smaller of the two items in the brackets.

For surfaces in the southern hemisphere sloped toward the equator, with $\psi = 180$ degrees, the equations are

$$\overline{R}_{\mathrm{D}} = \frac{\cos(\varphi + \Sigma)\ \cos\delta\ \sin\omega_s' + (\pi/180)\omega_s'\ \sin(\varphi + \Sigma)\ \sin\delta}{\cos\varphi\ \cos\delta\ \sin\omega_s + (\pi/180)\omega_s\ \sin\varphi\ \sin\delta} \tag{2.29}$$

and

$$\omega_s' = \min\begin{bmatrix} \cos^{-1}(-\tan\varphi\ \tan\delta) \\ \cos^{-1}(-\tan(\varphi + \Sigma)\ \tan\delta) \end{bmatrix} \tag{2.30}$$

$$\omega_s = \cos^{-1}(\tan\varphi\ \tan\delta). \tag{2.31}$$

The numerator of Eqs. (2.26) and (2.29) is the extraterrestrial radiation on the tilted surface, and the denominator is that on the horizontal surface. Each of them is obtained by integration of Eq. (2.13) over the appropriate time period, from true sunrise to sunset for the horizontal surface, and from apparent sunrise to apparent sunset on the tilted surface.

The R_{D} was calculated by Duffie and Beckman depending on angle difference $\varphi - \Sigma$ and latitude φ, and its values were included in [12].

For a known value of ratio R_{D} can be determined direct solar radiation on tilted surface from Eq. (2.12):

$$I_{\mathrm{D},\Sigma} = R_{\mathrm{D}} I_{\mathrm{D}}. \tag{2.32}$$

The procedure for calculating total solar radiation $I_{\mathrm{T},\Sigma}$ is by summing the contributions of the direct radiation, the components of the diffuse radiation, and the radiation reflected from the ground.

The diffuse radiation and the radiation reflected from the ground can be evaluated using the isotropic diffuse model of the sky proposed by Liu and Jordan [13] and extended by Klein [14]. The diffuse radiation on the tilted surface $I_{\mathrm{d},\Sigma}$ is defined by

$$I_{\mathrm{d},\Sigma} = \frac{1}{2}(1 + \cos\Sigma) I_{\mathrm{d}}, \tag{2.33}$$

TABLE 2.1 Typical Values of Ground Diffuse Reflectance

Ground Characteristic	ρ_g
Plowing	0.2
Verdure ground	0.3
Sandy desert	0.4
Snow	0.7

where I_d is the diffuse radiation on the horizontal surface.

The radiation reflected from the ground on the tilted surface $I_{r,\Sigma}$ is given by formula

$$I_{r,\Sigma} = \frac{1}{2}(1 - \cos\Sigma)\rho_g I_T, \tag{2.34}$$

where ρ_g is the diffuse reflectance of the ground (Table 2.1) [15] and I_T is the total solar radiation on the horizontal surface.

Consequently, total solar radiation on the tilted surface is the sum of the three components:

$$I_{T,\Sigma} = R_D I_D + \frac{1}{2}(1 + \cos\Sigma)I_d + \frac{1}{2}(1 - \cos\Sigma)\rho_g I_T. \tag{2.35}$$

The third term of Eq. (2.35) can be neglected as suggested by Hottel and Woertz [16] because the combination of diffuse and ground-reflected radiation is assumed isotropic.

The prediction of collector performance requires information on the solar energy absorbed by the collector absorber plate. Eq. (2.35) can be modified to give the absorbed radiation S by multiplying each term by the appropriate transmittanceabsorptance product $(\tau\alpha)$ as

$$S = I_D R_D(\tau\alpha)_D + I_d(\tau\alpha)_d\left(\frac{1 + \cos\Sigma}{2}\right) + \rho_g I_T(\tau\alpha)_g\left(\frac{1 - \cos\Sigma}{2}\right), \tag{2.36}$$

where $(1 + \cos\Sigma)/2$ and $(1 - \cos\Sigma)/2$ are the view factors from the collector to the sky and from the collector to the ground, respectively.

In addition to the regular variations, there are also substantial irregular variations. Of them, perhaps the most significant for engineering purposes are the day-to-day fluctuations because they affect the amount of energy storage required within a solar energy system. Thus, even a complete record of past radiation can be used to predict future radiation only in a statistical sense. Therefore design methods usually rely on approximate averages, such as monthly means of daily insolation. To estimate these cruder data from other measurements are easier than to predict a shorter-term pattern of radiation.

2.3 PREDICTION OF SOLAR RADIATION USING IMPROVED BRISTOW–CAMPBELL MODEL

Bristow and Campbell [17] proposed a method for estimating the daily I_T from diurnal temperature range ($t_M - t_m$) and the atmospheric transmittance ρ. The ratio between I_T and I_0 is calculated as a function of ($t_M - t_m$), which can be expressed as,

$$\frac{I_T}{I_0} = \rho = A\left[1 - \exp\left(-B(t_M - t_m)^C\right)\right], \tag{2.37}$$

where I_T is the total daily solar radiation; I_0 is the extraterrestrial radiation; ρ is the daily total atmospheric transmittance; A is the maximum radiation expected on a clear day, being distinctive for each location and depending on air quality and altitude; coefficients B and C control the rates at which A is approached as the temperature difference increases; t_M is the maximum air temperature; and t_m is the minimum air temperature.

This simple model neglects other factors that affect the amount of solar radiation that reaches the earth's surface, such as relative humidity, cloud cover, etc. Improved Bristow–Campbell (IBC) model considers the influencing factors of surface-solar radiation. So, more meteorological variables (e.g., t_M, t_m, $R_{H,}$ and OP) should be employed to represent the actual atmospheric transmittance. The IBC model is proposed as follows [18]:

$$I_0 = 37.54 \times \left(\frac{L_m}{L}\right)^2 (\omega_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s), \tag{2.38}$$

where I_0 is the daily extraterrestrial insolation incident on a horizontal surface in MJ/(m^2·day); ω_s is the solar angle at sunset (half-day length), in rad, computed using Eq. (2.31); δ is the solar declination, in rad; φ is the latitude of the location of interest, in rad; L_m is the mean value of the distance from the sun to earth, in km; and L is the distance from the sun to earth, in km.

The solar radiation at the top of the atmosphere can be calculated as

$$\frac{I_T}{I_0} = (b_0 + b_1 \sin w + b_2 \cos w + b_3 R_H + b_4 \mathrm{OP}) \times \left[1 - \exp\left(-b_5(t_M - t_m)^{b_6}\right)\right] \tag{2.39}$$

where R_H is the relative humidity; OP is the occurrence of precipitation; $w = 2\pi j/365$; and j is the Julian day.

The ratio L_m/L is known as the correction factor for the sun–earth distance, which can be obtained from equation [19]

$$\frac{L_m}{L} = \sqrt{1.00011 + 0.034221 \cos\xi + 0.034221 \sin\xi + 0.000719 \cos 2\xi + 0.000077 \sin 2\xi}. \tag{2.40}$$

The daily angle ξ, in rad, is calculated as a function of the Julian day ($\xi = 2\pi(j - 1)/365$). Then, the coefficients of the IBC model (b_0, b_1, b_2, b_3, b_4,

b_5, and b_6) can be obtained by minimizing the sums of the squares of deviations between observed and expected values. These derivatives are numerically computed using finite differences and the Newton−Raphson algorithm can be used for multivariate nonlinear optimization. The procedure can be easily implemented using Solver application of the Excel software. The detailed procedures for calculating the model parameters for IBC model can be seen in Meza et al. [20] and Pan et al. [21].

One additional factor that can be considered to improve the estimations of solar global radiation is the altitude of the station. Solar radiation that reaches the earth's surface is influenced by altitude above sea level due to the diminishing of the layer of air upon it. As a result, with the same meteorological conditions, higher locations receive more global solar radiation than at sea level.

The IBC model is easy to use in any location where measurements of temperature, precipitation, and relative humidity are available and present a simple solution that can be used as proxy for relative humidity in case that variable is not been measured.

Other solar radiation prediction models use the artificial intelligence methods including multilayer perception neural network, radial basis neural network, and generalized regression neural network, which have been recently discussed and tested by Wang et al. [18].

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