4. Solar radiation on tilted surfaces

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Learning Outcomes

After studying this chapter, readers will be able to:

- define the direct, diffuse and reflected solar radiation on inclined surface
- know the meaning of clearness index
- calculate the hourly and monthly solar radiation on surface of various orientations and tilt angles
- explain how the orientation and tilt angle of a surface affects the incident solar radiation
- understand how the choice of orientation and tilt angle of a pv panel affects its performances
- determine the optimum tilt angle of a pv panel, taking into account the latitude of the location, the planned application and the time period that the solar system is intended to be used

Knowledge of the solar radiation received by an inclined surface is necessary for most applications and studies involving solar systems. Generally, as weather stations only provide the total solar radiation on the horizontal plane, a method to calculate the radiation on an inclined surface at an hourly or monthly basis is necessary. To this purpose, the following sections describe a methodology for the calculation of the solar radiation on inclined surfaces at hourly and monthly periods.

4.1 HOURLY RADIATION ON TILTED SURFACE

The solar radiation received by an inclined plane on the ground surface consists of three components: the direct radiation coming of the solar disk, the diffuse radiation derived from the sky vault, and the reflected radiation coming from the ground in the surrounding area (fig. 4.1).

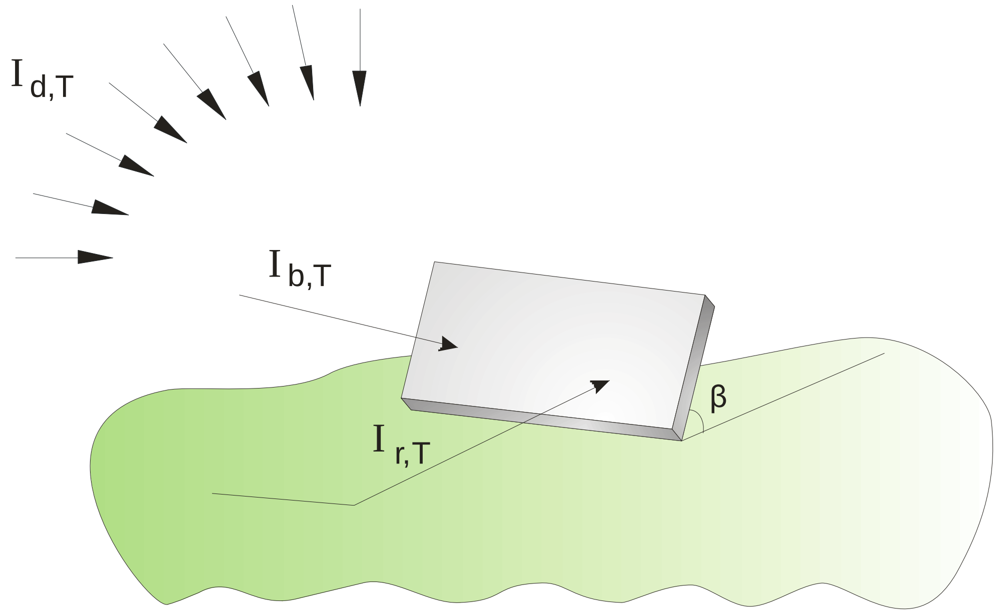

Figure 4.1 Direct, diffuse and reflected solar radiation on inclined surface.

The direct radiation a surface receives depends on the angle of incidence of the solar rays. The diffuse radiation received by the inclined surface does not depend on the orientation of the plane and does not come from the entirety of the sky vault or the ground nearby - it only comes from the part of the sky that the surface "sees". Therefore, for the calculation of solar radiation on an inclined surface, a conversion factor should be taken into account for each of the components [1].

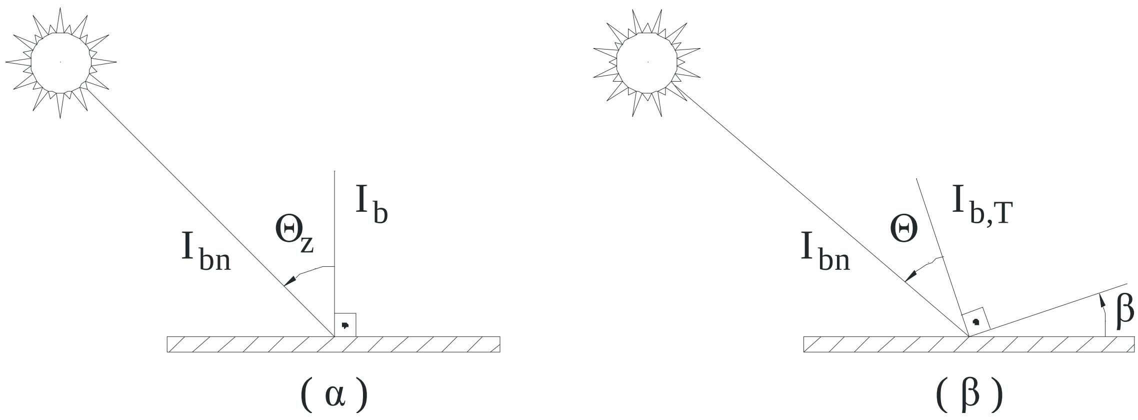

Figure 4.2 Determination of conversion factors for the direct solar irradiance. α) Irradiance on horizontal surface β) Irradiance on inclined surface

The conversion factor for the direct solar irradiance (R_b), is the ratio of the direct solar irradiance on the inclined surface ($I_{b,T}$), to that on a horizontal surface (I_b).

From Fig. 4.2 the following equation is easily deduced:

$$R_b = \frac{I_{b,T}}{I_b} = \frac{I_{b,n}\cos\theta}{I_{b,n}\cos\theta_Z} = \frac{\cos\theta}{\cos\theta_Z} \qquad (4.1)$$

Introducing $\cos\theta_Z$ from equation 3.5, into equation 4.1, the new equation can be written as:

$$R_b = \frac{\cos\theta}{\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta} \qquad (4.2)$$

From this equation, it becomes obvious that the value of R_b varies during the day and year for a given location.

The calculation of the component for the diffuse radiation is based on the assumption that the diffusion is isotropic, i.e. that it is uniformly received from the entire sky dome. The conversion factor for diffuse radiation (R_d) is the ratio of diffuse radiation incident on the inclined surface ($I_{d,T}$) to that on the horizontal plane (I_d). The diffuse radiation coming from the celestial dome, only a percentage reaches the inclined surface. This percentage is the ratio of the portion of celestial dome that the inclined surface "sees", to the entire hemispherical surface of the celestial dome. In the isotropic model and for an unshaded inclined surface on the ground, with slope β, the conversion factor is the view factor to the sky and is given by:

$$R_d = \frac{I_{d,T}}{I_d} = \frac{1+\cos\beta}{2} \qquad (4.3)$$

The conversion factor for the reflected radiation (Rr) is the ratio of reflected radiation incident on the inclined surface ($I_{r,T}$) to that on the horizontal (I_r). However, the reflected on the horizontal plane, is the product of the diffuse reflectance ρ of the surroundings and the total solar irradiance on the horizontal (I). As in the previous case, assuming that the reflected irradiance is isotropic, then for an inclined surface tilted at slope β from the horizontal, the conversion factor is the view factor to the ground and is given by:

$$R_r = \frac{I_{r,T}}{I\rho} = \frac{1-\cos\beta}{2} \qquad (4.4)$$

Thus, the total solar irradiance on the tilted surface I_T for an hour is the sum of three terms:

$$I_T = I_b R_b + I_d R_d + I\rho R_r \qquad (4.5)$$

Considering the equations 4.1, 4.3 and 4.4, the equation 4.5 can be rewritten as:

$$I_T = I_b \frac{\cos\theta}{\cos\theta_Z} + I_d \frac{1+\cos\beta}{2} + I\rho \frac{1-\cos\beta}{2} \qquad (4.6)$$

This equation can be used to calculate the hourly total solar irradiation on an inclined surface at slope β from the horizontal, where the angles θ and θ_Z correspond to the midpoint of the considered time. The reflectance ρ is usually taken 0.2, but when the surrounding area is covered with snow its value can be very high. Various values of ρ are given in Table 4.1

Table 4.1 Reflectance of different surfaces

Type of ground surface	Reflectance
Fresh snow	0.87
Dry sand	0.18
Wet sand	0.09
Coniferous forest	0.05
New concrete	0.33
Old concrete	0.23

Dividing both sides of equation 4.6 by I and considering the equation 4.1, the following equation can be written:

$$\frac{I_T}{I} = \left(1 - \frac{I_d}{I}\right) R_b + \frac{I_d}{I}\left(\frac{1+\sigma\upsilon\nu\beta}{2}\right) + \rho\frac{1-\sigma\upsilon\nu\beta}{2} \qquad (4.7)$$

Depending on the value of the hourly clearness index K, the ratio I_d /I is given by the following relations [2].

$$I_d/I = 1 - 0.09K \quad \text{for} \quad K \leq 0.22 \ (\alpha)$$

$I_d/I = 0.9511 - 0.1604K + 4.388K^2 - 16.638K^3 + 12.336K^4$ for $0.22<K<0.8$ (β)

$$I_d/I = 0.165 \text{ for } K > 0.8 \quad (\gamma) \qquad (4.8)$$

Hourly clearness index (K) is the ratio of total solar irradiation on a horizontal surface (I) to the hourly extraterrestrial irradiation on a horizontal surface (I_o). This index is considered to be the attenuation factor of the atmosphere. In general, when the atmosphere is clearer, a smaller fraction of irradiation is scattered. Additionally, the clearness index is a stochastic parameter, which is a function of time of year, season, climatic condition and geographic location.

$$K = \frac{I}{I_o} \qquad (4.9)$$

The calculation of the hourly extraterrestrial irradiation on a horizontal surface can be approximated by the following relationship if the zenith angle (θ_Z) corresponds to the midpoint of the considered time.

$$I_o = G_{on} \cos\theta_Z \qquad (4.10)$$

The extraterrestrial irradiation on a horizontal surface (I_o) can be obtained by integrating the equation 4.10 for a period between hour angles ω_1 and ω_2 [2].

$$I_{o(\omega_1-\omega_2)} = \int_{\omega_1}^{\omega_2} G_{on}\cos\theta_Z d\omega = \frac{12\cdot 3600}{\pi} G_{sc}(1+0.033\cos\frac{360\cdot n}{365})\cdot \left[\cos\phi\cos\delta(\sin\omega_2 - \sin\omega_1) + \frac{\pi(\omega_2-\omega_1)}{180}\sin\phi\sin\delta\right] \qquad (4.11)$$

Example 4.1

A PV panel is to be installed in Ioannina, Greece ($\phi = 39^o\ 42'$), at a slope of 35^o to the south. Using the isotropic diffuse model, calculate the hourly total solar irradiation as well as direct, diffuse and reflected, which will receive this panel for the hour 10 AM to 11 AM solar time, on 3 April. The hourly total solar irradiation on horizontal surface is 520 Wh/m^2 and the ground reflectance ρ = 0.2.

Solution

On April 3, n = 93 and from equation 3.2 the solar declination is:

$$\delta = 23.45\cdot\sin(360\frac{284+93}{365}) = 4.81^0$$

The solar hour angle (ω) can be considered representative, if calculated for the midpoint of the considered time. Hence, ω = - 22.5^o. With known values of δ, ω and ϕ, the solar zenith angle (θ_Z) can be calculated from equation 3.5:

$$\cos\theta_Z = \sin 4.81 \cdot \sin 39.7 + \cos 4.81 \cdot \cos 39.7 \cdot \cos(-22.5) = 40.37^0$$

From equation 2.5 the extraterrestrial solar irradiance G_{on} is calculated and then the hourly extraterrestrial irradiance on a horizontal surface (I_o) is given by:

$$I_o = 1365.6 \times \cos 40.37 = 1040.45 \text{ kW/m}^2$$

Here it is worth mentioning that I_o could be calculated from the relation 4.11 for a period of one hour from ω_1 (10AM) to ω_2 (11AM). For comparative reasons the value from this calculation is I_o = 1037.71 kWh/m^2. This value can be compared with 1040.45 kWh/m^2, assuming that the irradiance is constant for the required period of one hour.

K can be calculated by using equation 4.9.

$$K = \frac{520}{1040.46} = 0.5$$

Replacing the value of K in equation 4.8(β), the ratio I_d/I = 0.66. Hence:

$$I_d = 0.66 \times 520 = 343.2 \text{ Wh/ m}^2$$
$$I_b = 0.34 \times 520 = 176.8 \text{ Wh/ m}^2$$

At this point, the solar incident angle (θ) should be calculated. Knowing the solar zenith angle (θ_Z), the solar altitude can be calculated by equation 3.1 as follows:

$$h = 90 - 40.37 = 49.63^o$$

The solar azimuth angle (α) can be calculated via equation 3.14:

$$\sin\alpha = \frac{\cos 4.81 \cdot \sin(-22.5)}{\cos 49.63} = -36.07^0$$

Given that γ = 0, equation 3.16 yields:

$$\cos\theta = \cos 35 \cdot \cos 40.37 + \sin 35 \cdot \sin 40.37 \cdot \cos(-36.07) = 22.42^0$$

Replacing all known values in equation 4.6, the total irradiation on tilted surface (I_T) can be calculated:

$$I_T = 176.8\frac{\cos 22.42}{\cos 40.37} + 343.2\frac{1+\cos 35}{2} + 520 \cdot 0.2\frac{1-\cos 35}{2}$$

$$I_T = 214.52 + 312.17 + 9.4 = 536.1 \ \ Wh/m^2$$

Consequently, the total irradiation on PV panel is 537.27 Wh/m^2, the direct is 214.52 Wh/m^2, the diffuse is 312.17 Wh/m^2 and the reflected is 9.4 Wh/m^2.

4.2 MONTHLY RADIATION ON TILTED SURFACE

The same procedure such as the one used to develop equations for the I_T, may also be used for the calculation of the total daily solar irradiation (H_T) on a tilted surface. Since the diffuse and ground reflected irradiations are independent of the angle of incidence, the daily conversion factors are the same as the instantaneous factors given by equations 4.3 and 4.4.

Assuming that the isotropic model for the diffuse and global reflected radiation and in a manner analogous to equation 4.6, then the total daily solar irradiation on a tilted surface can be written as:

$$H_T = H_b R_b + R_d\left(\frac{1+\sigma\upsilon\nu\beta}{2}\right) + H\rho\left(\frac{1-\sigma\upsilon\nu\beta}{2}\right) \qquad (4.12)$$

In this case, R_b is the ratio of the daily beam radiation on the tilted surface $H_{b,T}$ to that on the horizontal surface H_b. Thus, for surfaces that are sloped toward the equator ($\gamma = 0$) in the northern hemisphere, this ratio can be determined by integrating equation 4.2 for the appropriate time period, from apparent sunrise ω_{sr}' to apparent sunset ω_{ss}' on the tilted surface and from true sunrise ω_{sr} to sunset ω_{ss} for the horizontal surface.

$$R_b = \frac{\int_{\omega'_{sr}}^{\omega'_{ss}} \sigma\upsilon\nu\theta d\omega}{\int_{\omega_{sr}}^{\omega_{ss}} \sigma\upsilon\nu\theta_Z d\omega} \qquad (4.13)$$

Given that ω_{sr}' = - ω_{ss}' and ω_{sr} = - ω_{ss}, these angles can have unified notation ω'_s and ω_s respectively [3]:

$$R_b = \frac{\cos(\phi-\beta)\cos\delta\sin\omega_s' + (\pi/180)\omega_s'\sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\sin\omega_s + (\pi/180)\omega_s\sin\phi\sin\delta} \tag{4.14}$$

where ω_s' is the sunset hour angle for the tilted surface, given by the following equation, and where "min" means the smaller of the two items in the brackets.

$$\omega_s' = \min\left\{\omega_s, ar\cos\left(-\tan\left(\phi-\beta\right)\varepsilon\phi\delta\right)\right\} \tag{4.15}$$

For solar applications, in many cases, it is necessary to calculate the monthly total solar irradiation on inclined surface. In such cases, an equation similar to 4.12 can be used, if the conversion factor is calculated for the typical day of the relevant month. Thus, the average monthly total solar irradiation on an inclined surface can be assessed using the following equation:

$$\overline{H}_T = \overline{H}_b\overline{R}_b + \overline{H}_d\left(\frac{1+\cos\beta}{2}\right) + \rho\overline{H}\left(\frac{1-\cos\beta}{2}\right) \tag{4.16}$$

Defining the conversion factor $\overline{R}$ as the ratio of the average monthly total solar irradiation on inclined surface $\overline{H}_T$ to that on a horizontal surface $\overline{H}$ results to:

$$\overline{\mathrm{H}}_{\mathrm{T}} = \overline{\mathrm{H}}\overline{R} \tag{4.17}$$

Using this simple equation, the $\overline{H}_T$ can be calculated if the $\overline{H}$ and $\overline{R}$ for a given month, site and tilt angle, are known. For some cities, tables are available with the values of $\overline{R}$, including all months and various tilt angles.

Similar with the equation 4.7, the equation 4.16 can be transformed to the following equation:

$$\frac{\overline{H}_T}{\overline{H}} = \left(1-\frac{\overline{H}_d}{\overline{H}}\right)\overline{R}_b + \frac{\overline{H}_d}{\overline{H}}\left(\frac{1+\cos\beta}{2}\right) + \rho\left(\frac{1-\cos\beta}{2}\right) \tag{4.18}$$

Several relations for the ratio $\frac{\overline{H}_d}{\overline{H}}$ have been proposed by various researchers [4-9], According to Liu and Jordan [9], this ratio can be calculated using the following equation:

$$\frac{\overline{H}_d}{\overline{H}} = 1.390 - 4.027\overline{K} + 5.531\overline{K}^2 - 3.108\overline{K}^3 \tag{4.19}$$

In this case, $\overline{K}$ is the clearness index given as the ratio of the monthly average daily of the total irradiation on a horizontal surface ($\overline{H}$) to the monthly average daily extraterrestrial irradiation ($\overline{H}_o$).

$$\overline{K} = \frac{\overline{H}}{\overline{H}_o} \qquad (4.20)$$

The monthly average daily extraterrestrial irradiation ($\overline{H}_o$), can be calculated by integrating the G_o over the period from sunrise (ω_{sr}) to sunset (ω_{ss}).

$$\overline{H}_o = \int_{\omega_{sr}}^{\omega_{ss}} G_o \cos\theta_Z d\omega \qquad (4.21)$$

If the solar constant is in W/m^2 and the equations 2.5 and 3.5 are taken into account, then the following equation will give the $\overline{H}_o$ in J/m^2:

$$\overline{\mathrm{H}}_o = \frac{24 \cdot 3600 \cdot G_{sc}}{\pi}\left(1 + 0.033\cos\frac{360n}{365}\right)\left(\cos\phi\cos\delta\sin\omega_s + \frac{\pi\omega_s}{180}\sin\phi\sin\delta\right) \quad (4.22)$$

The monthly average daily extraterrestrial irradiation $\overline{H}_o$ is a useful quantity and can be calculated by equation 4.22 for latitudes in the range +60^o to -60^o.

Example 4.2

Using the isotropic diffuse assumption, calculate the average monthly total solar irradiation on inclined PV panel at a slope of 40^o to the south, for a latitude of 37^o 06′ N. The ground reflectance is 0.2 and the monthly values of total irradiation on a horizontal surface are shown in table 4.2.

Solution

First, the mean monthly total solar irradiation for the inclined surface $\overline{H}_T$ will be calculated analytically for January and then in a similar manner can be calculated the corresponding values for the other months. For the mean January day, the solar declination can be calculated, considering the 17th from table 3.1. Thus for n = 17, the equation 3.2 gives:

$$\delta = 23.45 \cdot \sin(360\frac{284 + 17}{365}) = -20.92^0$$

Using the equation 3.10 the sunset hour angle ω_s is:

$$\omega_s = \arccos\theta(-\tan 37.1 \cdot \tan(-20.92) = 73.2^0$$

Since that δ and ω_s are now known, the monthly average daily extraterrestrial irradiation $\overline{H}_o$ is calculated from the equation 4.22:

$$\overline{H}_o = 146.31 \text{ kWh/m}^2$$

The clearness index $\overline{K}$ can be obtained from equation 4.20:

$$\overline{\mathrm{K}} = \frac{51}{146.31} = 0.35$$

The value of clearness index $\overline{K}$ is used to calculate $\frac{\overline{H}_d}{\overline{H}}$ from equation 4.19

$$\frac{\overline{H}_d}{\overline{H}} = 1.446 - 2.965 \cdot 0.35 + 1.727 \cdot (0.35)^2 = 0.62$$

The sunset hour angle ω'_s at the inclined surface is calculated by the equation 4.15 and is:

$$\omega'_s = \min\{73.2, \cos^{-1}(-\tan(37.1-40) \cdot \tan(-20.92))\} = \min(73.2^0, 91.1^0)$$

The $\overline{R}_b$ is calculated by equation 4.14 as:

$$\overline{R}_b = \frac{\cos(37.1-40) \cdot \cos(-20.92) \cdot \sin 73.2 + (3.14/180) \cdot 73.2 \cdot \sin(37.1-40) \cdot \sin(-20.92)}{\cos 37.1 \cdot \cos(-20.92) \cdot \sin 73.2 + (3.14/180) \cdot 73.2 \cdot \sin 37.1 \cdot \sin(-20.92)} = 2.09$$

Using the aforementioned values, the mean monthly total solar irradiation for the inclined surface $\overline{H}_T$, can be obtained for January, by using the equation 4.18.

$$\overline{H}_T = 69.62 \text{ kWh/m}^2$$

The results for the 12 months are shown in the table 4.2

Table 4.2

Month	H kWh/m^2	H_o kWh/m^2	H_d/H	R_b	H_T kWh/m^2
Jan.	51	146.31	0.62	2.09	69.62
Feb.	67.4	172.48	0.55	1.68	84.92
Mars	111	247.38	0.46	1.32	126.54
Apr.	149	294.60	0.38	1.02	147.51
May	193	343.48	0.32	0.84	169.84
June	205	347.10	0.29	0.77	170.15
July	212	350.30	0.28	0.80	180.20
Aug.	194	318.68	0.28	0.94	184.30
Sept.	161	258.90	0.27	1.19	181.93
Oct.	111	207.08	0.35	1.55	148.74
Nov.	75	151.50	0.40	1.97	116.25
Dec.	52	134.54	0.55	2.22	78.00

4.3 SOLAR RADIATION ON SURFACE OF VARIOUS ORIENTATIONS AND TILT ANGLES

The solar radiation incident on a surface depends, among other things, on its slope and its orientation. For a surface at a particular place, the increase of its slope results to the reception of more radiation during the winter than during the summer. Thus, for solar applications that require energy from solar panels mainly during the winter the slope should be large, while when the panels are used during the summer the inclination should be small.

For maximum energy availability during winter, summer and the entire year, a rule of thumb that applies to the collector slope is that this slope should respectively be approximately 10° to 15° greater than the latitude, approximately 10° to 15° smaller than the latitude, and equal to the latitude of the site. Hence, different sites/locations have different optimal slope angles for solar panels.

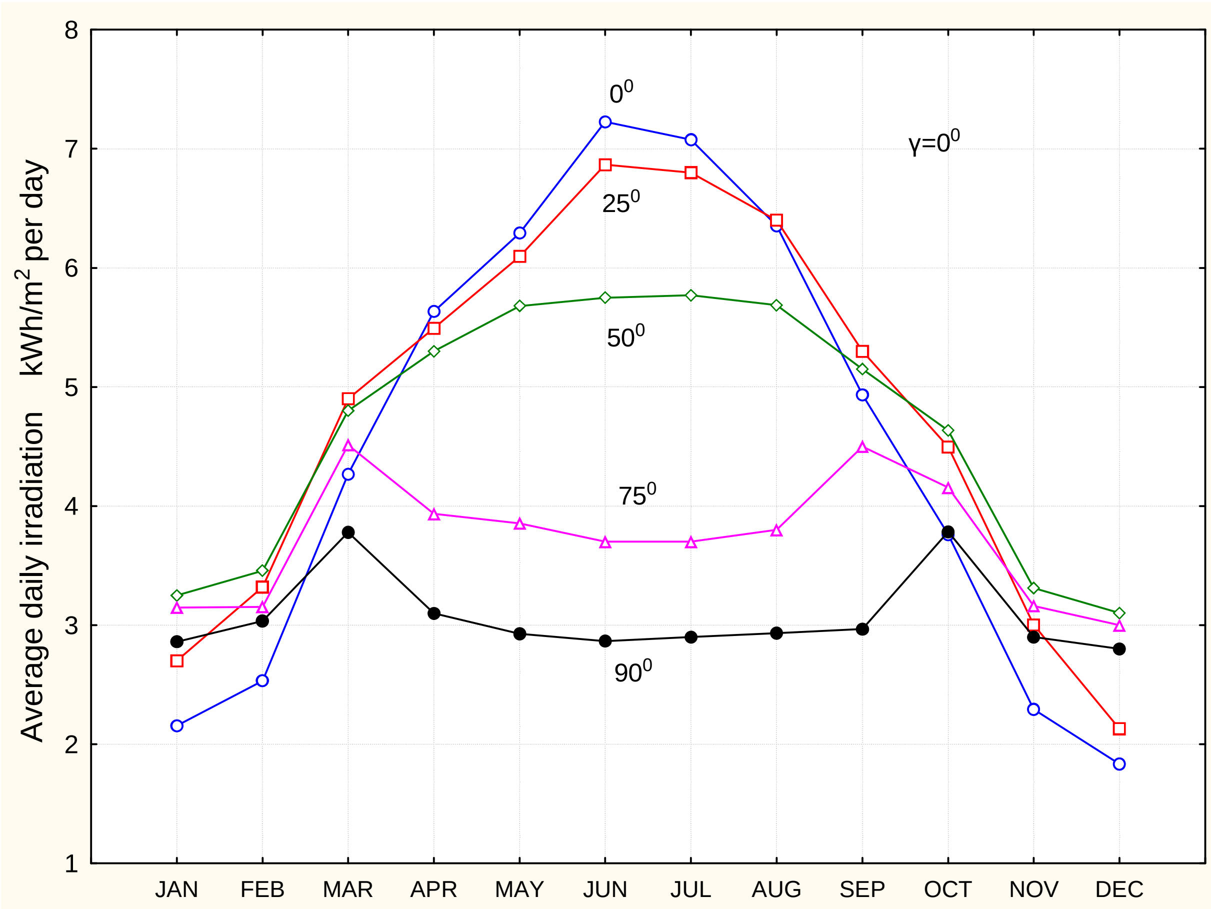

Figure 4.3 Effect of the receiving surface slope on monthly average daily irradiation for a latitude of 38^o, ground reflectance 0.2 and orientation due south (γ = 0).

Figure 4.3 shows the monthly average daily irradiation received by south facing surfaces of various slopes [10]. These values refer to latitude 38° N, ρ = 0.2 and are approximate. Nevertheless, these provide a complete picture of the slope's influence on the solar irradiation received by a surface. This figure confirms the rule of thumb mentioned earlier.

It is known that the tilt angle of the PV panel largely determines the received solar irradiance and is the primary factor that governs the power output of the panel. As the position of the sun on the celestial sphere changes during the day and follows a different path for each day of the year, it becomes apparent that the determination of an optimal tilt angle is essential for the optimal operation of every PV system.

In order to illustrate the effect of slope of a photovoltaic panel to the electrical power output, an experiment was conducted at a specific time, in the morning of a day in Athens [11]. The power of the photovoltaic panel was 55 W_p, its orientation due south and the tilt angles were chosen to change from 0° to 90° in an interval of 10°. The experimental results are plotted in Fig. 4.4. As can be seen from this figure, the optimal tilt angle is around 60°. Beyond the optimal tilt angle, the power output gradually drops. The optimum tilt angle of the example demonstrated in Fig. 4.4 is high because it is morning (10:34 am), thus the solar altitude is low.

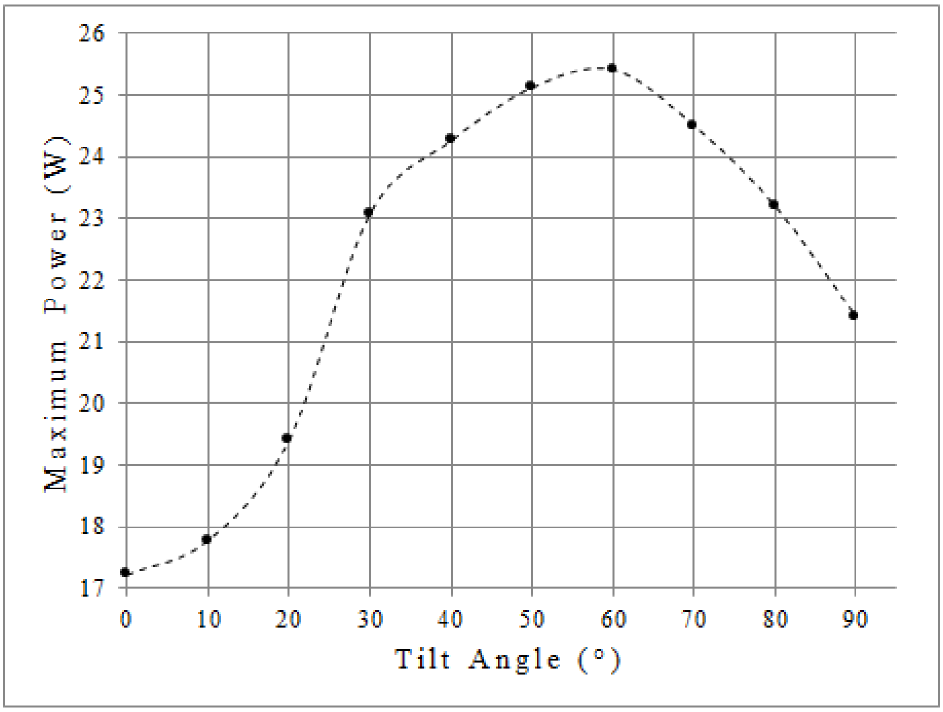

Figure 4.4 Experimental results of the maximum power output of the photovoltaic panel at different tilt angles for Athens ($\phi=38^0$N).

Another factor that affects the solar radiation incident on a surface is the orientation of the surface. Considering that solar radiation is symmetrical at solar noon, then the best orientation for a fixed solar panel is the south ($\gamma = 0$). Deviations of the azimuth angle by 10° or 20° east or west of the south will have little influence on the annual solar energy collected. The orientation of a solar photovoltaic panel also has an effect on the time that it will receive the solar radiation. For example, a solar panel located at southeast will receive the largest amount of solar radiation in the morning.

Figure 4.5 shows the monthly mean daily irradiation on the horizontal and on four vertical surfaces (south, east, north and west) at latitude 38^o N [10]. A feature that this figure displays is that all the curves except that of the south facing surface have a maximum corresponding to the summer solstice, while the south facing surface has two maxima that correspond to the spring and autumnal equinox. In addition, it can be noticed that the south facing vertical surface will receive larger amounts of solar irradiation during the winter months, while the horizontal surface predominates during the summer months.

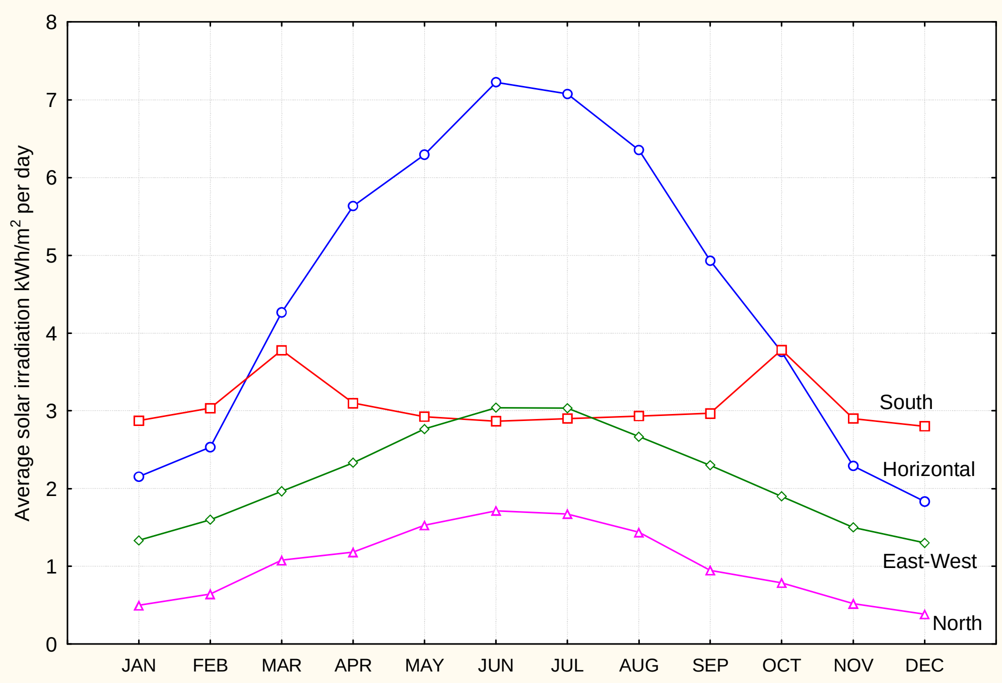

Figure 4.5 Monthly mean daily irradiation on horizontal and four vertical surfaces, (south, east, north and west) at latitude 38° N.

For a more detailed description, let us start with the curve representing the solar irradiation on the vertical north-facing surface. During the winter months, the sun rises and sets to the south of east-west line and therefore there is not any direct solar irradiation on this surface. Conversely, during the summer months, due to the longer day length, a small amount of solar irradiation falls on this surface.

The curves representing the solar irradiation on vertical west and east-facing surface have greater values than that of vertical north facing surface. During the summer months the sun rises and sets to the north of east-west line, the apparent path of the sun is longer and therefore the incident solar irradiation on these surfaces is higher than that of vertical north facing surface.

The horizontal surface receives much more irradiation during the summer because the solar altitude is maximized.

The curve representing the solar irradiation on vertical south facing surface has a completely different form compared to the other curves. The two maximum values correspond to the spring and autumnal equinox. During the winter months, due to the low solar altitude, this surface receives the greatest amount of solar irradiation. The combination of low solar altitude with the short day length during the winter results to the superiority of the vertical south facing surface compared to the other orientations.

The rule of thumb mentioned above for the inclination of a fixed panel gives good results when applied in small solar installations. However, in the case of large solar installations, even a slight change in slope corresponds to a large shift on the incident irradiation. In addition, with photovoltaic systems where the cost of solar panels is high, it is necessary to study the optimum slope for each particular application. For example, if the photovoltaic panels will be used for a grid-connected system that remains functional throughout the year, the optimum slope should be calculated with the maximum solar irradiation incident on the panels over the whole year in mind. This optimum panel angle is usually close to the latitude angle. However, in the case of a stand-alone photovoltaic system with batteries as an energy storage, the criterion may not be the total solar irradiation, but the daily irradiation during the month with the least solar irradiation, in order to minimize the energy storage requirements. For example, in the northern hemisphere, December is considered to be the month with the lowest irradiation, so the panel angle will be greater than the latitude angle. Generally, the optimum panel slope should be determined by the latitude of the location, the planned application and the time period that the solar system is intended to be used.

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