

6. Solar Irradiance Modeling

Since most solar energy conversion systems are installed in a non-horizontal position, irradiance data for tilted surfaces are in great demand for solar energy research and applications.

Available solar radiation data typically consists of global horizontal data only. To yield estimates of the irradiance on tilted surfaces, these data often have to be modelled from available recordings of horizontal irradiation.

→ We need conversion models for estimating the irradiance on inclined planes.

It is current practice for evaluating the irradiation on a tilted surface to decompose the solar radiation into the components direct beam, sky diffuse and ground-reflected radiation:

$$G_t = G_{bt} + G_{dt} + G_{rt}, \quad (6.1)$$

where the indices denote tilted (t), beam (b), diffuse (d) and reflected (r) radiation, respectively.

The components then are treated separately (Fig. 6.1).

The models generally differ in the treatment of the diffuse radiation component. The representation of the distribution of radiance in the sky hemisphere is difficult. Assumptions used to describe it are main causes of errors in these models.

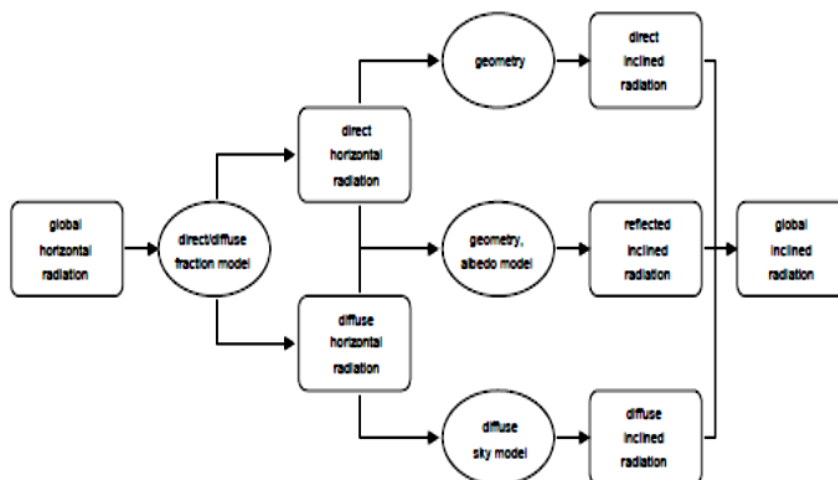


Fig. 6.1. Conversion steps for estimating global radiation on tilted surfaces from global horizontal radiation.

The modeling of direct irradiance is straightforward and identical in all models (more difficult only for time integrated values).

Ground-reflected radiation: Also difficult to estimate, but of lesser impact due to absolute lower values (only in certain circumstances of higher importance).

Requirement of knowledge of different radiation components (diffuse and direct)

Components have to be inferred from available data (usually only global)

→ Need for additional model for the diffuse/direct fractions of global radiation

6.1 Direct Radiation Component

$$G_{bt} = G_{bn} \cos \theta. \quad (6.2)$$

With $G_b = G_{bn} \cos \theta_z$ it is:

$$G_{bt} = G_b \frac{\cos \theta}{\cos \theta_z}. \quad (6.3)$$

In the literature, the ratio $\cos \theta / \cos \theta_z$ often is referred to as the geometric factor R_b .

To force the application of Eq. 6.3 to realistic cases, in computer algorithms $\cos \theta$ should be replaced by $\max(0, \cos \theta)$.

6.2 Ground-Reflected Radiation Component

Assumption: Ground reflects irradiation isotropically:

$$G_{rt} = G \rho \frac{1 - \cos \beta}{2}, \quad (6.4)$$

where $\rho = G_r / G$ is the albedo (reflectance) of the surface.

Important: Appropriate albedo (variations in time, snow!),

Variation in albedo with zenith angle

Second order: anisotropic effects

Modifications are only necessary when strong directional variations in reflectance or local obstructions to the horizon occur.

6.3 Diffuse Radiation Component

Different sky conditions:

- overcast: isotropic distribution is good approximation
- broken cloudiness: very difficult, largest variations
- clear sky: anisotropic effects

Plot: Hay and McKay



$$G_{dt} = G_d \frac{(1 + \cos \beta)}{2} M_3 M_4, \quad (6.7)$$

where $M_3 = 1 + F \sin^3(\beta/2)$, $M_4 = 1 + F \cos^2 \theta \sin^3 \theta_z$ and $F = 1 - (G_d/G)^2$.

For overcast skies $F = 0$ (isotropic distribution), for clear skies: $F = 1$ (same as the Temps and Coulson model)

T.M. Klucher (1979). Evaluation of models to predict insolation on tilted surfaces. *Solar Energy*, 23, 111-1144.

4. Hay and Davies, 1980:

Approach: Overcast \rightarrow no direct radiation \rightarrow isotropic distribution

Absence of atmosphere \rightarrow only direct radiation: $G_t = G(\cos \theta / \cos \theta_z)$

The actual state between these extremes is determined by the anisotropy index $\kappa = I_b/I_o$, giving the atmospheric transmissivity (diffuse radiation is divided into circumsolar and isotropically distributed diffuse radiation)

κ gives the portion of diffuse radiation to be treated as circumsolar and isotropic, respectively (no horizon brightening is considered);

G_{dt} is a linear combination based on the transmissivity for direct radiation.

$$G_{dt} = G_d \left\{ \kappa \frac{\cos \theta}{\cos \theta_z} + (1 - \kappa) \frac{(1 + \cos \beta)}{2} \right\} \quad (6.8)$$

J. Hay and J.A. Davies (1980). Calculation of the solar radiation incident on an inclined surface. Proc. First Canadian Solar Radiation Data Workshop (Ed. by J.E.Hay and T.K.Won). Canadian Atmospheric Environment Service, Downsview, Ontario. 59-72.

5. Perez et al., 1983:

Approach: Diffuse radiation is described by an isotropic background superimposed by two regions of enhanced radiation:

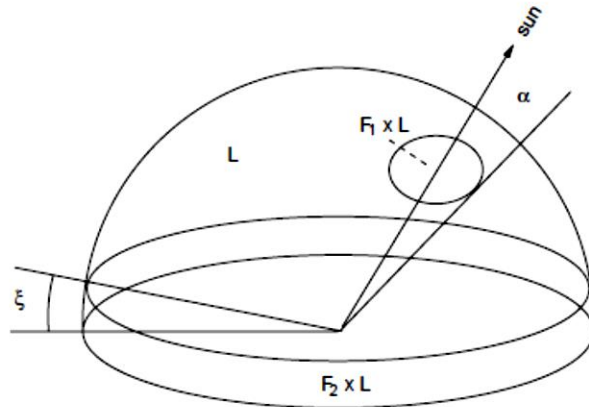


Fig. 6.2. Anisotropic components of diffuse sky radiation. Enhancements are due to circumsolar radiation and horizon brightening.

- a disk of variable size around the sun
- a horizontal band of variable height at the horizon.

The enhanced radiation is described by:

F_1 : multiplier for circumsolar region (i.e. F_1 times the background (isotropic) radiation,

F_2 : multiplier for horizon region.

$$G_{dt} = G_d \left\{ \frac{\left(\frac{1+\cos\beta}{2} \right) + a(F_1 - 1) + b(F_2 - 1)}{1 + c(F_1 - 1) + d(F_2 - 1)} \right\}, \quad (6.9)$$

where $a(\theta)$ and $b(\theta)$ are solid angles covered by the circumsolar disk and the horizon band, respectively multiplied by their average incidence on the considered plane (view factors to the receiver). $c(\theta_z)$ and d are the equivalent quantities for the horizontal (view factors to the horizontal).

F_1 and F_2 describe the sky condition and vary independently with the irradiance condition!

For isotropic distributions it is: $F_1 = F_2 = 0$.

Parameterized by:

- zenith angle θ_z ,
 - diffuse horizontal radiation G_d ,
 - $\epsilon = (G_{bn} + G_d)/G_d$.
- Large amount of categories (for each $[\theta_z, G_d, \epsilon]$ interval), i.e. 240 different pairs of F_1, F_2 parameters

R. Perez, J.T. Scott and R. Stewart (1983). An anisotropic model for diffuse radiation incident on slopes of different orientations, and possible applications to CPCs. Proceedings of ASES, Minneapolis, MN., 883-888.

R. Perez, R. Seals, P. Ineichen, R. Stewart and D. Menicucci (1987). A new simplified version of the Perez diffuse irradiance model for tilted surfaces. *Solar Energy*, **39**, 221-231.

6. Skartveit and Olseth, 1986:

A. Skartveit and J.A. Olseth (1986). Modelling slope irradiance at high latitudes *Solar Energy*, **36** 333-344.