Chapter

Computing the Global Irradiation over the Plane of Photovoltaic Arrays: A Step-by-Step Methodology

Oswaldo A. Arraez-Cancelliere, Nicolás Muñoz-Galeano and Jesús M. López-Lezama

Abstract

The quality of solar resource data is critical for the economic and technical assessment of solar photovoltaic (PV) installations. Understanding uncertainty and managing weather-related risk are essential for successful planning and operating of solar electricity assets. The input information available for PV designers is usually restricted to 12 monthly mean values of global horizontal irradiation (GHI) and average temperature, which characterize solar climate of locations. However, for calculating the energy production of a photovoltaic system, the global irradiation over the plane of the PV array is necessary. For this reason, this book chapter presents a methodology to appropriately determine the global irradiation over the plane of photovoltaic arrays. The methodology describes step by step the necessary equations for processing the data. Examples with numerical results are included to better show the data processing.

Keywords: global horizontal irradiation (GHI), photovoltaic (PV), energy production, solar resource, data processing

1. Introduction

Renewable energy resources have become a promissory alternative to overcome the problems related to high pollution and limited sources of conventional energy. So, the analysis of energy resources and their economic feasibility is a concern topic for researchers around the world [1–4]. In this context, photovoltaic power plants have become one of the most important renewable sources of energy that have rapidly spread in the last decade. However, the assessment of the solar resource is not a topic usually approached by engineers and researchers due to the complexity in the process of computing the data, being extensive when the global horizontal irradiation is processed to obtain the global tilde irradiation. Therefore, this book chapter provides a step-by-step methodology for computing the global irradiation over the plane of photovoltaic arrays.

The quality of solar resource data is critical for economic and technical assessment of solar power installation. Understanding uncertainty and managing weather-related risk are essential for successful planning and operating of solar electricity assets. High-quality solar resource and meteorological data can be obtained by two approaches: high-accuracy instruments installed at a meteorological station and complex solar meteorological models, which are validated using high-quality ground instruments [5].

The input information available for PV designers is usually restricted to the 12-monthly mean values of global horizontal irradiation (GHI) and average temperature, which characterize solar climate of locations. However, the global irradiation over the plane of the PV array is necessary to calculate the energy production of a photovoltaic system.

The assessment of radiation arriving on an inclined surface, using global horizontal data as input, raises two main problems; first, to separate the GHI into their direct and diffuse components (decomposition) and, second, from them, to estimate the radiation components falling on an inclined surface (transposition) [6]. To solve these problems, it is important to describe in detail parameters such as declination angle, solar hour angle, solar zenith, solar altitude, solar azimuth, angle of incidence, solar constant, extraterrestrial irradiance over the horizontal surface, clearness index, and diffuse fraction index [6–8].

As regards decomposition models, in Ref. [9], authors reviewed and compared four decomposition models for monthly average of horizontal daily irradiation: a linear relationship proposed by Page [10], two polynomial equations defined by the authors of Refs. [11, 12], and a local correlation proposed by Macagnan et al. [13]. The authors of Ref. [9] stand out for the Page decomposition model of Ref. [10] in combination with the Perez transposition model [13] as a good performance combination used for passing from global horizontal irradiation to effective in-plane irradiance when it is started from monthly average of daily irradiation values. After applying the decomposition models, direct, diffuse, and albedo components of irradiation can be obtained.

For obtaining radiation components falling on an inclined surface, geometric considerations can be taken into account [9]. In Ref. [9], eight transposition models were reviewed, obtaining the best results using the Perez model [13]. Similar results were obtained in Ref. [14], where four transposition models were compared and validated with two-year data measured at site, and Liu and Jordan isotropic sky model is used in this book chapter due to its simplicity of implementation and good results reported in Ref. [15].

This book chapter describes in detail a methodology to determine the global irradiation over the plane of photovoltaic arrays. The chapter is organized as follows: Section 2 contains the proposed methodology, Section 3 includes experimental results that include data processing, and Section 4 presents the conclusions.

2. Proposed methodology

The proposed methodology includes the data processing and also the definitions to understand it. Therefore, some basic definitions are presented below:

2.1 Declination angle (δ)

It is the angle between the equatorial plane and a straight line drawn between the center of the Earth and the center of the sun. It may be considered as approximately constant over the course of any day. It can be calculated using Eq. (1), where d_n is the day number counted from the beginning of the year [7].

$$\delta = 23.45° \times sin\left[\frac{360 \times (d_n + 284)}{365}\right] \tag{1}$$

2.2 Solar hour angle (ω)

It is the difference between noon and the selected moment of the day in terms of a 360° rotation in 24 h. ω is equal to 0 at midday of each day, and it is counted as negative in the morning and positive in the afternoon. The solar hour angle is given as:

$$\omega = 15 \times (T_{solar}(h) - 12) \tag{2}$$

$$T_{solar}(h) = T_{local}(h) + \frac{4(L_{st} - L_{loc}) + EoT}{60} \tag{3}$$

$$EoT\ (\ min\ ) = 9.87\,sin\,2B - 7.53\,cos\,B - 1.5\,sin\,B \tag{4}$$

$$B_n = \frac{360}{365}(d_n - 81) \tag{5}$$

$$L_{st} = 15 \times \Delta T_{gmt} \tag{6}$$

where T_{solar} and T_{local} are the solar time and the local clock time, respectively. L_{st} and L_{loc} are the standard meridian for the local time zone and the longitude of the location (east positive and west negative). ΔT_{gmt} is the local time zone (e.g., Bogotá, −5). EoT stands for equation of time, which is the time difference between the apparent solar time for people and the real mean solar time, and takes into account the perturbation of the earth's rotation [7].

2.3 Solar zenith (θ_{zs}) and solar altitude (γ_s)

Solar zenith is the angle between the vertical and the incident solar beam, and it can also be described as the angle of incidence of beam radiation on a horizontal surface [6]. The complement of the zenith angle is called the solar altitude, γ_s. These angles can be calculated using Eq. (7) and are function of the declination angle (δ), the latitude (ϕ) (north positive and south negative), and the true solar time (ω).

$$cos\,\theta_{zs} = sin\delta\ sin\phi + cos\delta\ cos\delta\ cos\omega = \ sin\,\gamma_s \tag{7}$$

$$\gamma_s = 90 - \theta_{zs} \tag{8}$$

Eq. (7) can be used to find the sunrise angle (ω_s) since at sunrise $\gamma_s = 0$, hence.

$$\omega_s = -\,cos^{-1}(-\,tan\,\delta tan\phi) \tag{9}$$

In accordance with the sign convention, ω_s is always negative. The sunset angle is equal to $-\omega_s$, and the length of the day is equal to:

$$T_d(hour) = \frac{2 \times abs(\omega_s)}{15°} \tag{10}$$

2.4 Solar azimuth (ψ_s)

It is the angle between the meridians of the locations and the sun. It can also be described as the angular displacement from noon to the projection of beam radiation on the horizontal plane. The solar azimuth is given by:

$$\cos \psi_s = \left(\frac{\sin \gamma_s \times \sin \phi - \sin \delta}{\cos \gamma_s \cos \phi} \right) \quad (11)$$

In the Northern Hemisphere, true solar is the reference of the system, and it is defined as positive toward the west, that is, in the evening, and negative toward the east, that is, in the morning [6]. In **Figure 1**, the solar zenith, solar altitude, and solar azimuth are described.

2.5 Angle of incidence (θ_i)

Most practical applications require the position of the sun relative to an inclined plane to be determined. The angle of solar incidence between the sun's rays and the normal to the surface is given by:

$$\begin{aligned} \cos(\theta_i) = {} & \sin(\delta)\sin(\varnothing)\cos(\beta) - [sign(\varnothing)]\sin(\delta)\cos(\varnothing)\sin(\beta)\cos(\alpha) \\ & + \cos(\delta)\cos(\varnothing)\cos(\beta)\cos(\omega) + [sign(\varnothing)]\cos(\delta)\sin(\varnothing)\sin(\beta)\cos(\alpha)\cos(\omega) \\ & + \cos(\delta)\sin(\alpha)\sin(\omega)\sin(\beta) \end{aligned} \quad (12)$$

where β is the tilt of the inclined plane (the angle formed with the horizontal), and α is the surface azimuth angle conventionally measured clockwise from the south (See **Figure 2**) [8]. The $sign(\varnothing)$ function is 1 when the latitude is greater than 0 and is -1 otherwise.

2.6 Solar constant (B_0)

It is the amount of solar radiation received at the top of the atmosphere on a normal plane at the mean Earth-sun distance [6]. A good approximation of this value is:

$$B_0 = 1367\ W/m^2 \quad (13)$$

Extraterrestrial irradiance over the horizontal surface ($B_0(0)$): Extraterrestrial radiation over a horizontal surface varies over the day, and it is given by:

$$B_0(0) = B_0 \times \left[1 + 0.033\cos\left(\frac{360}{365} d_n\right)\right] \cos\theta_{zs} \quad (14)$$

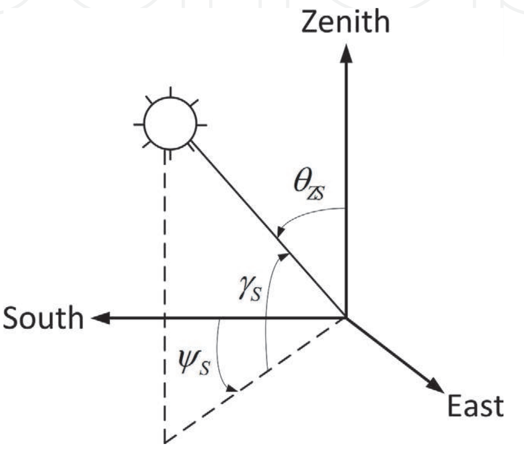

Figure 1.
Position of the sun relative to a fixed point on the earth defining the solar azimuth (ψ_s), the solar zenith (θ_{zs}), and the solar altitude (γ_s).

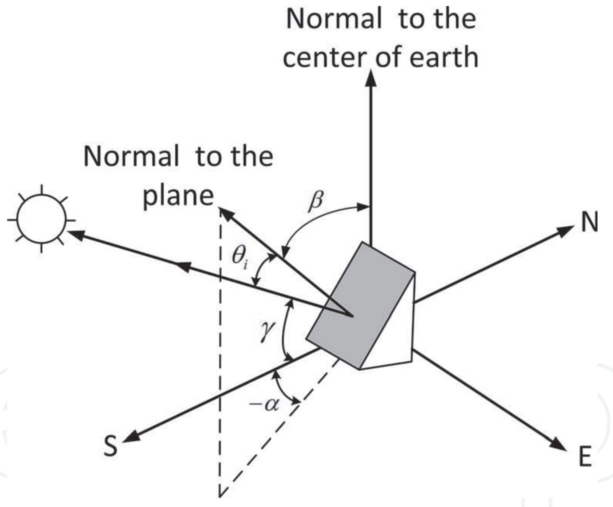

Figure 2.
Definition of angles used as coordinates for an element of sky radiation to an inclined plane of tilt β and oriented to α.

If Eq. (14) is integrated over the day, the following expression is obtained:

$$B_{0d}(0) = \frac{24}{\pi} B_0 \left[1 + 0.033\, cos\left(\frac{360}{365} d_n\right)\right] \left[cos\phi\, cos\delta\, \sin\omega_s + \frac{\pi}{180}\, \omega_s\, sin\, \phi sin\delta\right] \quad (15)$$

Hence, average daily extraterrestrial irradiation in a month over a surface is obtained by:

$$B_{0dm}(0) = \frac{1}{d_{n2} - d_{n1} + 1} \sum_{d_{n1}}^{d_{n2}} B_{0d}(0) \quad (16)$$

The value calculated in Eq. (16) is used to estimate the clearness index (K_{Tm}) [2].

2.7 Clearness index (K_{Tm})

It is the relation between the solar radiation at the Earth's surface and the extraterrestrial radiation over the horizontal plane. The clearness index K_{Tm} for each month is given by:

$$K_{Tm} = \frac{G_{dm}(0)}{B_{0dm}(0)} \quad (17)$$

where $G_{dm}(0)$ is the average daily horizontal global irradiation of a month, which is usually an input value [6].

2.8 Diffuse fraction index (K_d)

It is the relation between the diffuse radiation over the horizontal plane and the global radiation over the horizontal plane. This index is widely used on decomposition models to separate the global radiation into its direct and diffuse components.

$$K_{dm} = \frac{D_{dm}(0)}{G_{dm}(0)} \quad (18)$$

The modeling process for calculating the effective in-plane hourly irradiation when starting from monthly average of horizontal daily irradiation and using monthly average daily irradiance profiles is shown in **Figure 3** [9].

The daily irradiance profile can be defined in terms of irradiance divided by daily irradiation and on assuming that the profile of the extraterrestrial horizontal solar radiation translates directly into the profile of the diffuse component while an empirical correction is needed for global radiation [11]. The following equations describe the model to calculate the daily irradiance profile starting from daily average monthly values:

$$G(0) = r'_G \times G_{dm}(0) \tag{19}$$

$$D(0) = r'_D \times D_{dm}(0) \tag{20}$$

$$B(0) = G(0) - D(0) \tag{21}$$

with

$$r'_D = \frac{B_0(0)}{B_{0d}(0)} = \frac{\pi}{T} \times \left(\frac{\cos\omega - \cos\omega_s}{\frac{\pi}{180} \times \omega_s \times \cos\omega_s - \sin\omega_s} \right) \tag{22}$$

$$r'_G = r'_D \times (a + b \times \cos\omega) \tag{23}$$

$$a = 0.409 - 0.5016 \times \sin(\omega_s + 60) \tag{24}$$

$$b = 0.6609 + 0.4767 \times \sin(\omega_s + 60) \tag{25}$$

where ω and ω_s are expressed in degrees, and T is the day length, usually expressed in hours (24 h). The unit of indexes r_D and r_G is T^{-1}, and they can be used to calculate irradiation during short periods centered on the considered instant ω. Subscripts "d" and "m" refer to the daily and monthly average of daily values, respectively.

The diffuse component of the average daily irradiation, $D_{dm}(0)$, is derived from a decomposition model consisting of an empirical relationship between the clearness index, K_{Tm}, and the diffuse fraction, K_{dm}. In Ref. [9], the authors review and compare four decomposition models for monthly average of horizontal daily

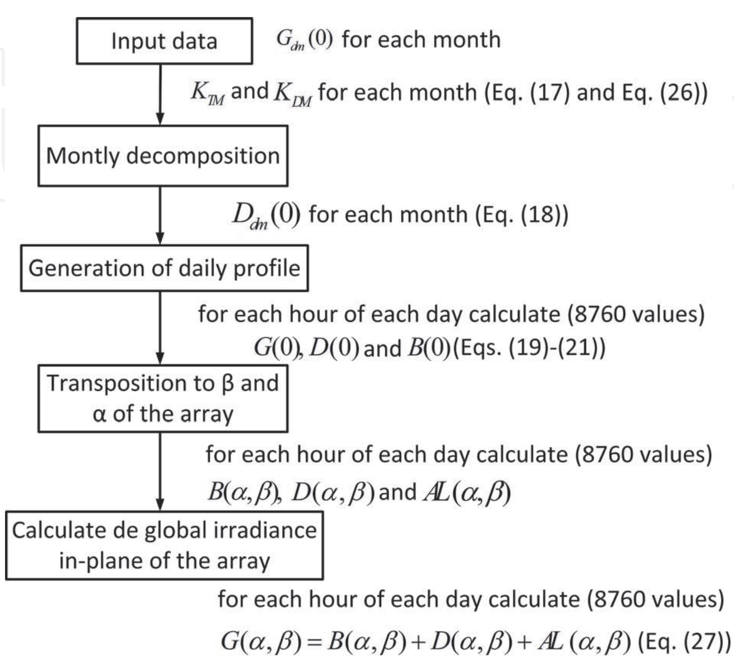

Figure 3.
Calculation of daily irradiation on an inclined surface.

irradiation: a linear relationship proposed by Page [10], two polynomial equations defined by the authors of Refs. [11, 12], and a local correlation proposed by Macagnan et al. [13]. The authors stand out the Page decomposition model in combination with the Perez transposition model [13] as a good performance combination used for passing from global horizontal irradiation to effective in-plane irradiance when it is started from monthly average of daily irradiation values.

The decomposition model proposed by Page consists of a linear equation that correlated the diffuse fraction index and the clearness index using data from locations situated between 40°N and 40°S, and it is given by:

$$K_{dm} = 1 - 1.13K_{Tm} \tag{26}$$

Once the global horizontal irradiance is separated into direct and diffuse components and the daily irradiance profile is obtained, it is necessary to calculate the effective irradiance on the plane of the array. The irradiance over the plane with a tilt β, in degrees, and oriented to angle α, conventionally measured clockwise from the south, can be obtained by:

$$G(\beta, \alpha) = B(\beta, \alpha) + D(\beta, \alpha) + AL(\beta, \alpha) \tag{27}$$

where G, B, D, and AL represent global, direct, diffuse, and albedo components, respectively. The irradiance components over the plane are given by:

$$B(\beta, \alpha) = B(0) \times r_B \tag{28}$$

$$D(\beta, \alpha) = D(0) \times r_D \tag{29}$$

$$AL(\beta, \alpha) = G(0) \times r_{AL} \tag{30}$$

The beam transposition factor is calculated straightforward from simple geometric considerations [9]:

$$r_B = \frac{max\,(0,\, cos\,\theta_i)}{cos\,\theta_{zs}} \tag{31}$$

Assuming isotropic albedo radiation, the corresponding transposition factor is given by:

$$r_{AL} = \rho \frac{1 - \ cos\,\beta}{2} \tag{32}$$

where ρ is the ground reflection factor. The albedo radiation is scarcely relevant and rarely measured. A general reflection value of 0.2 is considered since this is extendedly used on practice [9].

The diffuse transposition factor depends on the assumption made for the sky radiance distribution. In Ref. [9], eight transposition models are reviewed, obtaining the best results using the Perez model. Similar results are obtained in Ref. [14], where four transposition models are compared and validated with two-year data measured at site, and the most accurate results were obtained by the Hay and Davies transposition model and the Perez transposition model. In this work, the Liu and Jordan isotropic sky model is used due to its simplicity of implementation and good results as reported in Ref. [15].

In the transposition model proposed by Liu and Jordan, the diffuse radiation is given by an isotropic component coming from the entire celestial hemisphere. The diffuse transposition factor is given by:

$$r_D = \frac{1 + \cos\beta}{2} \quad (33)$$

In summary, the global irradiation over the tilted plane is calculated by:

$$G(\beta, \alpha) = B(0) \times r_B + D(0) \times r_D + G(0) \times r_{AL} \quad (34)$$

3. Experimental results: Data processing

Santa Cruz del Islote in Colombia was used as a location for the case study. Data that consist on the monthly average daily global horizontal irradiance (G_{dm}) and the monthly average ambient temperature ($T_{amb,m}$) were provided by Solargis through its pvPlanner platform, see **Table 1**.

A MATLAB routine was used to compute the monthly global irradiance over the horizontal and over the plane. Results were also compared with the data that can be processed from Solargis, and **Table 2** shows the results obtained. Comparison shows that the results are good enough for the purpose of this work.

Location	**Islote de Santa Cruz, Colombia**	
Latitude	9.79	
Longitude	−75.859167	
Time zone (GTM)	−5	
Tilt	10	Plane inclination
Azimuth	0	Plane orientation (South = 0°; West 90°)
GRF	0.2	Ground reflection factor (0–1) Default = 0.2
Month	Daily sum of global irradiation [Wh/m^2]	Average diurnal (24-h) air temperature [°C]
January	5922.6	27.8
February	6271.4	27.6
March	6267.7	27.6
April	5906.7	27.7
May	5367.7	27.9
June	5396.7	28.5
July	5587.1	28.7
August	5538.7	28.5
September	5363.3	28.2
October	5025.8	27.9
November	4970.0	27.8
December	5200.0	28.0
Average	5568.1	28.0

Table 1.
Meteorological input parameters [16].

	Global horizontal irradiation (kWh/m^2) Solargis	Global horizontal irradiation (kWh/m^2) calculated	Dev (%)	Global tilted irradiation (kWh/m^2) Solargis	Global tilted irradiation (kWh/m^2) calculated	Dev (%)
January	183.6	182.0	−0.88%	201.9	198.6	−1.65%
February	175.6	174.2	−0.81%	186.9	184.3	−1.41%
March	194.3	193.0	−0.68%	198.5	196.2	−1.14%
April	177.2	176.1	−0.65%	175	172.9	−1.17%
May	166.4	165.2	−0.70%	160.1	158.8	−0.83%
June	161.9	160.8	−0.71%	153.6	152.6	−0.65%
July	173.2	172.0	−0.69%	165.3	163.9	−0.84%
August	171.7	170.6	−0.65%	167.8	166.1	−1.03%
September	160.9	159.8	−0.70%	162	160.1	−1.17%
October	155.8	154.4	−0.91%	162.4	159.5	−1.79%
November	149.1	147.7	−0.96%	160.5	157.1	−2.13%
December	161.2	159.7	−0.93%	177.8	174.1	−2.09%
Year	2030.9	2015.3	−0.77%	2071.8	2044.1	−1.34%

Table 2.
Global horizontal and tilted irradiations.

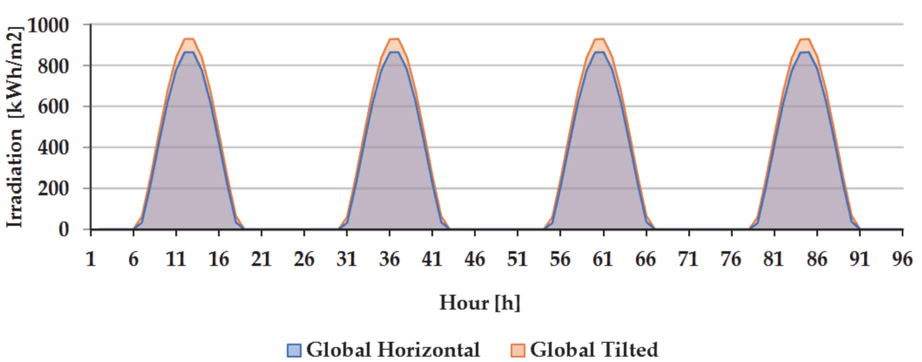

Figure 4.
Daily global irradiation calculated for "Islote de Santa Cruz."

In **Figure 4**, it is shown the daily global profile on the horizontal and on the tilted plane for the first 4 days of the year calculated for the selected location. As expected, global tilde irradiation is higher than the global horizontal irradiation.

4. Conclusions

This book chapter presented a methodology that describes in detail the data processing to obtain the global irradiation over the plane of photovoltaic arrays. The methodology includes definitions and equations necessary to perform the processing of the data. The following parameters were described and along with their equations: declination angle, solar hour angle, solar zenith, solar altitude, solar azimuth, angle of incidence, solar constant, extraterrestrial irradiance over the horizontal surface, clearness index, and diffuse fraction index.

The obtention of the global irradiance over a tilde plane requires decomposition models, which provide direct, diffuse, and albedo components of irradiation. This book chapter provides global horizontal irradiation to effective in-plane irradiance when it is started from monthly average of daily irradiation values.

This book chapter is extensive in the use of geometric considerations. This is due to the fact that input data are global horizontal irradiation and average temperature, while output data are the global irradiation over a tilde PV plane. Therefore, equations and schemes were provided for facilitating the explanation.

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