SUPPORTING INFORMATION

Performance evaluation of grid-connected photovoltaic system under climatic conditions of the Isthmus of Tehuantepec

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Section I.

The calculation of the energy received on the surface of a panel, at a specific tilt angle, is determined using the horizontal surface radiation at the specific site. This methodology is based on calculating the diffuse and direct components independently, whether hourly, daily, or as a monthly average. Global radiation is the sum of both components [1]. In this work, the average monthly radiation on the surface of the photovoltaic generator was determined at a tilt angle of 16°. The methodology used is described step by step below.

1. Determination of daily extraterrestrial radiation on the horizontal surface for each month.

The hourly radiation outside the Earth's atmosphere, reaching the horizontal surface, is determined in J/m2/day, as

$$H_{oh} = \frac{24x3600G_{sc}}{\pi}\left(1 + 0.033\cos\frac{360n}{365}\right)x\left(\cos\phi\cos\delta\sin\omega_s + \frac{\pi\omega_s}{180}\sin\phi\sin\delta\right) \quad (1)$$

where G_{sc} is the solar constant, n is the ordinal day or Julian day, ϕ is the latitude, δ is the declination, and $\omega_s$is the sunset hour angle, which is determined as

$$\omega_s = \cos^{-1}(-\tan\delta\tan\phi) \quad (2)$$

The monthly average daily extraterrestrial radiation, H_{oh}, can be calculated with the same equation, using n and δ for the mean day of the month.

The declination is determined by the following equation:

$$\delta = \left(\frac{180}{\pi}\right)(0.006918 - 0.399912\cos B + 0.070257\sin B - 0.006758\cos 2B + 0.000907\sin 2B - 0.002697\cos 3B + 0.00148\sin 3B) \quad (3)$$

where B is

$$B = (n-1)\frac{360}{365} \quad (4)$$

2. Calculation of the average clearness index from the average extraterrestrial and average global radiation on a horizontal surface

The monthly average clearness index $\overline{K}_T$ is defined as the ratio between the monthly average daily radiation on the horizontal surface $\overline{H}_h$ and the monthly average daily extraterrestrial radiation $\overline{H}_{oh}$, and can be determined by

$$\overline{K}_T = \frac{\overline{H}_h}{\overline{H}_{oh}} \quad (5)$$

$\bar{H}_h$ is experimentally obtained as the monthly average of global radiation on the horizontal surface.

3. Determination of the average diffuse and direct components on a horizontal plane

The monthly average global irradiance on a horizontal plane is the sum of the direct and diffuse components:

$$\bar{H}_h = \bar{H}_{bh} + \bar{H}_{dh} \quad (6)$$

where $\bar{H}_{bh}$ is the monthly average of direct radiation on the horizontal plane, and $\bar{H}_{dh}$ is the monthly average of diffuse radiation on the horizontal plane.

The diffuse fraction of solar radiation is a function of the clearness index, and for the case of the diffuse fraction of the monthly average radiation, it can be expressed as

$$\bar{F}_d = \frac{\bar{H}_{dh}}{\bar{H}_h} \quad (7)$$

for sunset angles $\omega_s \leq 81.84°$ and $0.3 \geq \bar{K}_T \leq 0.8$

$$\frac{\bar{H}_{dh}}{\bar{H}_h} = 1.391 - 3.560\bar{K}_T + 4.189\bar{K}_T^2 - 2.137\bar{K}_T^3 \quad (8)$$

and for sunset angles $\omega_s > 81.84°$ and $0.3 \geq \bar{K}_T \mathrm{T} \leq 0.8$

$$\frac{\bar{H}_{dh}}{\bar{H}_h} = 1.311 - 3.022\bar{K}_T + 3.427\bar{K}_T^2 - 1.821\bar{K}_T^3 \quad (9)$$

The direct component on the horizontal plane is determined by subtracting the diffuse radiation component, $\bar{H}_{dh}$, from the global radiation on the horizontal surface, $\bar{H}_h$, that is, by solving Equation (6).

4. Determination of the monthly average radiation components on the tilted surface

Similarly, the total monthly average radiation on a tilted surface is equal to the sum of the monthly average direct radiation components on a tilted surface and the monthly average diffuse radiation on the tilted surface:

$$\bar{H}_t = \bar{H}_{bt} + \bar{H}_{dt} \quad (10)$$

where $\bar{H}_t$ is the monthly average total radiation on a tilted surface, $\bar{H}_{bt}$is the monthly average direct radiation on a tilted surface, and $\bar{H}_{dt}$ is the monthly average diffuse radiation on the tilted surface.

The daily direct ratio is defined as the quotient between the monthly average direct radiation on the tilted surface ($\bar{H}_{bt}$) and the monthly average direct radiation on a horizontal plane ($\bar{H}_{bh}$):

$$\frac{\bar{H}_{bi}}{\bar{H}_{bh}} = \frac{\bar{H}_{bn}cos\theta}{\bar{H}_{bn}cos\theta_z} \cong \frac{cos\theta}{cos\theta_z} \equiv R_b \quad (11)$$

where θ and θ_z are the normal incidence angle and the horizontal plane incidence angle, respectively.

The relationship between the beam radiation on the tilted surface and that on a horizontal surface during the month is Rb, or the geometric correction factor, which is equal to

$$\bar{R}_b = \frac{\bar{H}_{bi}}{\bar{H}_{bh}} \quad (12)$$

$\bar{R}_b$ is a function of atmospheric transmittance and can be estimated using the Liu-Jordan model. Considering that, in the Northern Hemisphere, the optimal azimuth is equal to 0°, corresponding to a surface oriented completely south, the relationships of $\cos\theta \ y \ \cos\theta_z$ can be simplified.

$$\bar{R}_b = \frac{\cos(\phi-\beta)\cos\delta \ \sin\acute{\omega}_s + \left(\frac{\pi}{180}\right)\acute{\omega}_s \sin(\phi-\beta) \ \sin\delta}{\cos\phi \ \cos\delta \ \sin\omega_s + (\frac{\pi}{180})\omega_s \ \sin\phi \ \sin\delta} \quad (13)$$

where $\acute{\omega}_s$ is the sunset hour angle for the tilted surface for the average day of the month, which is given by

$$\acute{\omega}_s = min\begin{bmatrix} \cos^{-1}(-\tan\phi \ \tan\delta) \\ \cos^{-1}(-\tan(\phi-\beta) \ \tan\delta) \end{bmatrix} \quad (14)$$

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

Finally, the monthly average beam radiation on the tilted surface would be

$$\bar{H}_{bi} = \bar{R}_b \ \bar{H}_{bh} \quad (15)$$

The Liu and Jordan model, or isotropic sky model, considers that radiation on the tilted surface includes three components: beam, isotropic diffuse, and diffusely reflected solar radiation from the ground.

A surface tilted at a slope β from the horizontal has a sky view factor:

$F_{c-s} = \left(\frac{1+\cos\beta}{2}\right)$ (16)

The tilted surface has a view factor to the ground:

$$F_{c-g} = \left(\frac{1-\cos\beta}{2}\right) \quad (17)$$

and if the surroundings have a diffuse reflectance of ϱg for total solar radiation, the reflected radiation from the surroundings on the surface will be $\bar{H}_h\rho_g\left(\frac{1-\cos\beta}{2}\right)$.

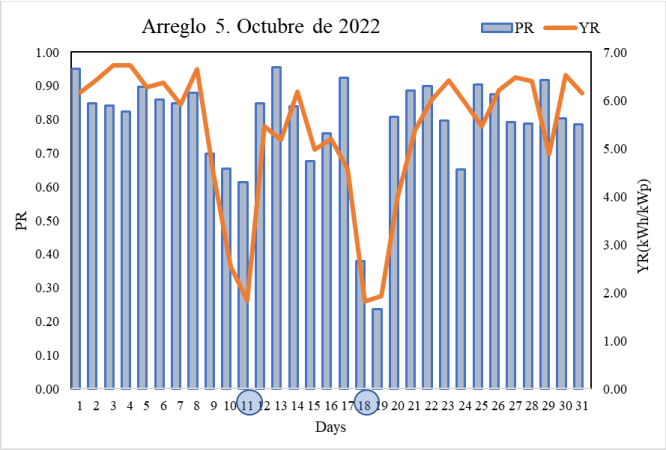
Finally, the monthly average total radiation on the tilted surface is determined as

$\bar{H}_i = \bar{R}_b\,\bar{H}_{bh} + \bar{H}_{dh}\left(\frac{1+\cos\beta}{2}\right) + \bar{H}_h\rho_g\left(\frac{1-\cos\beta}{2}\right)$ (18)

Section II.

The overall loss coefficient (PR) is a parameter that indicates how much energy is ultimately delivered to the grid; consequently, it also reflects energy losses, i.e., energy that did not reach the grid. These losses are divided into those associated with direct current (DC) energy and alternating current (AC) energy. Analyzing DC energy losses in more detail, we can consider several factors that simultaneously influence them: irradiance irregularity due to cloudiness, the rise in module temperature when radiation and ambient temperature are very high, and so on. Sometimes, high wind speeds can reduce module temperature; however, moderate gusts can lead to greater dust deposition on the surface of the panels. Rain contributes to panel cleaning, although on rainy days, irradiance is usually low. Therefore, to quantitatively estimate a particular effect, a more precise study is required to minimize the effects of other variables. Nevertheless, it is possible to correlate the energy produced on a day or a month with the specific environmental conditions of that period. Figure S1 in the supplementary information presents a graph comparing PR and YR values for array five for the 31 days of October (Figure S1a) and the 30 days of November (Figure S1b). In October, there was rain on days 11 and 18, and cloudiness on days 9, 10, and 19. The correlation between the reference yield YR (low irradiance on the day) and low PR values can be observed, which is completely logical.

As seen, in the days following the rainy period, with moderate to high YR and assuming the panels are clean, PR values are relatively higher. At the beginning of October, the system was clean due to September rainfall, and after the rainy days in October, PR values also increased. If we compare the PR values of October (two rainy days) and November (zero rainy days), for days with similar irradiance—even on a day with lower irradiance in the month when it did rain—we can appreciate the influence of panel cleaning on PR (although we cannot ignore that panel temperatures may be different. For example, in October, we chose day 13 with YR: 5.18 h and PR: 0.96, and day 23 with YR: 6.42 h and PR: 0.80; in November, we chose days 24, with YR: 6.45 h and PR: 0.77, and 25, with YR: 6.43 h and PR: 0.72. As observed, for similar YR values, PR in November is lower. Taking October PR = 0.80 with YR = 6.42 h as a reference and November PR = 0.72 with YR = 6.43 h, a 10% decrease in energy produced in November is observed.



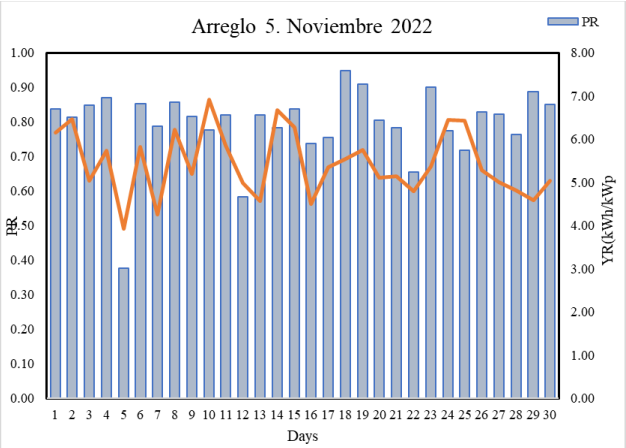


Figure S1. PR and irradiance behavior for different days: (S1a) in October and (S1b) in November.

References

1. Duffie, J. A. and Beckman, W. A. Solar Engineering of Thermal Processes. John Wiley & Sons, Inc., Hoboken, New Jersey, **2013**.