## Appendix A. Irradiance Calculation

When sizing a PV system, the first step is to define the hourly irradiance (W/m2) on the location where the system is to be installed. In this work, hourly irradiance has been calculated using monthly average irradiation (kWh/m2) obtained from meteorological data. Hourly irradiance can be estimated by applying a series of transformations to irradiation data (Duffie and Beckman, 2013).

Firstly, it is necessary to calculate a series of angles which will condition the amount of energy received from the sun. These angles are declination (δ) and the sunset hour angle (ωs), both in radians

$δ=0.006918-0.399912\cos(\left(B\right))+0.070257\sin(\left(B\right))-0.006758\cos(\left(2B\right))+0.000907\sin(\left(2B\right))-0.002697\cos(\left(3B\right))+0.00148\sin(\left(3B\right)) $ (1)

$\cos(\left(ωs\right))=-\tan(\left(φ\right))\tan(\left(δ\right)) $ (2)

where *B* is given by

$B=(n-1)\frac{2π}{365} $ (3)

*φ* is the latitude angle (positive to the North) and *n* is the day of the year, usually considered as:

Table A1. Day considered as monthly representative.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec |
| n | 17 | 47 | 75 | 105 | 135 | 162 | 198 | 228 | 258 | 288 | 318 | 344 |

Then monthly extra-terrestrial irradiation, Hoh(Wh/m2) incident on a horizontal plane can be calculated:

$Ho=\frac{24}{π} I\_{sc}\left[1+0.033 cos⁡\left(2π\frac{n}{365}\right)\right] (\cos(\left(φ\right))\cos(\left(δ\right))\sin(\left(ω\_{s}\right))+ω\_{s} sin\left(φ\right)\sin(\left(δ\right)))$ (4)

where all the angles are expressed in radians and$ I\_{sc}$ is the solar constant (1367 W/m2).

Secondly, with the above values known, it is possible to calculate irradiance values on any surface. This irradiance will have three basic components: beam radiation ($H\_{b})$, diffuse radiation ($H\_{d})$ and reflected radiation. These components are calculated as described below.

With the monthly global irradiation ($\overbar{H}$) data and the monthly values of $\overbar{H\_{o}}$, the clearness index $\overbar{K\_{T}}$is obtained:

$\overbar{K\_{T}}=\frac{\overbar{H}}{\overbar{H\_{o}}} $ (5)

The ratio between diffuse and global irradiation is calculated as suggested by Erbs et al. (1982):

$\frac{\overbar{H\_{d}}}{\overbar{H}}=1.391-3.560 \overbar{K\_{T}}+4.189 \overbar{K\_{T}}^{2}-2.137 \overbar{K\_{T}}^{3} for ω\_{s}\leq 81.4º and 0.3\leq \overbar{K\_{T}}\leq 0.8$ (6)

$\frac{\overbar{H\_{d}}}{\overbar{H}}=1.311-3.022 \overbar{K\_{T}}+3.427 \overbar{K\_{T}}^{2}-1.821 \overbar{K\_{T}}^{3} for ω\_{s}>81.4º and 0.3\leq \overbar{K\_{T}}\leq 0.8$ (7)

With these coefficients, monthly values of the beam and diffuse irradiation will be defined as:

$\overbar{H\_{d}}=\frac{\overbar{H\_{d}}}{\overbar{H}} ∙\overbar{ H} $ (8)

$\overbar{H\_{b}}=\overbar{ H}-\overbar{H\_{d}}$ (9)

Finally, these monthly irradiations are converted to hourly irradiance values. Knowing that the Earth spins at 15º per hour, the sunrise and sunset solar hours for *n* can be determined:

$Sunrise=12+\left(\frac{-ω\_{s}∙180}{π∙15}\right) $ $(10)$

$Sunset=12+\left(\frac{ω\_{s}∙180}{π∙15}\right) $ $(11)$

These sunrise and sunset hours define the number of sun hours for each *n*. Consequently, in the interval between sunrise and sunset, hourly irradiance can be determined under the assumption of the isotropic sky as follows:

$I\left(t\right)=I\_{b }\left(t\right)R\_{b}+I\_{d}\left(t\right)\left(\frac{1+cosβ}{2}\right)+\left(I\_{b }\left(t\right)+I\_{d}\left(t\right)\right)ρ\left(\frac{1-cosβ}{2}\right)$ $(12)$

where $I\_{b }(t)$ and $I\_{d}(t)$ are hourly beam and diffuse irradiances, $β$ is the PV module tilt angle and ρ the albedo.

The coefficient $R\_{b}$ is the ratio of total radiation on tilted surface to that on the horizontal surface, considering the azimuth angle of the PV modules as 0º (facing south):

$R\_{b}=\left.\frac{\sin(δ\sin(\left(φ-β\right)+\cos(δ)\cos(ω\cos(\left(φ-β\right)))))}{\sin(φ)\sin(δ)+\cos(φ\cos(δ\cos(ω)))} \right.$ $(13)$

The ratios of hourly total to daily total radiation ($r\_{t})$ and hourly diffuse to daily diffuse radiation ($r\_{d})$ must be determined:

$r\_{t }=\left(\frac{π}{24}\right)\left(a+b\cos(ω)\right)\left(\frac{\cos(ω)-\cos(ω\_{s})}{\sin(ω\_{s}- ω\_{s})\cos(ω\_{s})}\right)$ $(14)$

$a=0.409+0.5016\sin(\left( ω\_{s}-\frac{π}{3}\right)) $ $(15)$

$b=0.6609+0.4767\sin(\left( ω\_{s}-\frac{π}{3}\right))$ $(16)$

$r\_{d }=\left(\frac{π}{24}\right)\left(\frac{\cos(ω)-\cos(ω\_{s})}{\sin(ω\_{s}- ω\_{s})\cos(ω\_{s})}\right)$ $(17)$

The value of $ω (rad)$ refers to the hour angle considered in between the sunrise-sunset interval, therefore the ratios’ values will depend on day *n* and solar hour considered.

Hourly global ($I\_{T}(t))$ and hourly diffuse ($I\_{d}(t))$ irradiances in (W/m2) are given by:

$I\_{T}\left(t\right)=r\_{t} \overbar{H}$ $(18)$

$I\_{d}\left(t\right)=r\_{d} \overbar{H\_{d}} $ $(19)$

Finally, the hourly beam irradiance will be:

$I\_{b}\left(t\right)=I\_{T}\left(t\right)-I\_{d}\left(t\right)$ $(20)$

Summing the three components as in Eq. 12 the hourly distribution of irradiance for the day *n* is obtained. The values obtained for Albamix network are depicted in Table A1.

Table A1. Irradiation curves for July In Albamix.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Time** | **W/m2** | **hora** | **W/m2** | **hora** | **W/m2** | **hora** | **W/m2** |
| 4.75 | 0.02 | 8.5 | 151.29 | 12.25 | 250.70 | 16 | 126.75 |
| 5 | 2.57 | 8.75 | 163.18 | 12.5 | 248.92 | 16.25 | 114.31 |
| 5.25 | 5.17 | 9 | 174.70 | 12.75 | 245.96 | 16.5 | 101.88 |
| 5.5 | 12.52 | 9.25 | 185.73 | 13 | 241.86 | 16.75 | 89.55 |
| 5.75 | 22.11 | 9.5 | 196.18 | 13.25 | 236.66 | 17 | 77.42 |
| 6 | 32.25 | 9.75 | 205.96 | 13.5 | 230.40 | 17.25 | 65.55 |
| 6.25 | 42.90 | 10 | 214.98 | 13.75 | 223.15 | 17.5 | 54.02 |
| 6.5 | 54.02 | 10.25 | 223.15 | 14 | 214.98 | 17.75 | 42.90 |
| 6.75 | 65.55 | 10.5 | 230.40 | 14.25 | 205.96 | 18 | 32.25 |
| 7 | 77.42 | 10.75 | 236.66 | 14.5 | 196.18 | 18.25 | 22.11 |
| 7.25 | 89.55 | 11 | 241.86 | 14.75 | 185.73 | 18.5 | 12.52 |
| 7.5 | 101.88 | 11.25 | 245.96 | 15 | 174.70 | 18.75 | 5.17 |
| 7.75 | 114.31 | 11.5 | 248.92 | 15.25 | 163.18 | 19 | 2.57 |
| 8 | 126.75 | 11.75 | 250.70 | 15.5 | 151.29 | 19.25 | 0.02 |
| 8.25 | 139.11 | 12 | 251.30 | 15.75 | 139.11 |  |  |

This figures reflect the irradiance in a single PV system. As the area of every panel is equal to 1.6 m2, the power supplied at every time of the day result as multiplying the previous values by this area. As there are some other efficiency factors (pump efificiency=0.85; asynchronous motor efficiency =0.80 and converter efficiency=0.95) involved in calculating the net energy transferred to water by one single modulus is presented in Table A1. In this Figure, it is also shown the restriction of number of irrigation hours equal to 7 (from 8.5 to 15.5 hours).



Figure A1. Net energy transferred to water by 1 single PV

# REFERENCES

Duffie, J.A., Beckman, W. A., (2013). “Solar Engineering of Thermal Processes”. 4th edition Wiley. ISBN: 978-0-470-87366-3.