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Resumo: A irradiância global horizontal é, tipicamente, a componente da radiação solar mais medida. Contudo, nas fases de projeto e instalação de sistemas de captação de energia solar, estes são instalados com uma certa inclinação de modo a optimizar a intercepção de radiação solar. Tendo isto em consideração, o presente trabalho baseia-se nas medidas de radiação solar efectuadas pela rede de medição do IPMA – Instituto Português do Mar e da Atmosfera, que consiste em 89 estações de medição ao longo do país. Com base na avaliação da disponibilidade de radiação solar global horizontal, efectuada em publicações anteriores, aplicou-se uma conhecida metodologia de modo a estimar radiação solar global numa superfície inclinada. Uma vez estimada a radiação solar global incidente na superfície com inclinação igual à latitude local, efectuou-se uma estimativa do potencial de produção de energia com recurso a um sistema solar fotovoltaico.

Abstract: Global Horizontal Irradiance is the most commonly component of solar radiation to be measured. However, when projecting and installing solar energy systems, those are not installed horizontally but at a certain angle to optimize solar radiation interception. With this in mind, the present work is based on the solar radiation data measured by IPMA's – Portuguese Institute for Sea and Atmosphere network, consisting in 89 measuring stations across the country. With basis on the assessment of Global Horizontal Irradiation availability performed in previous publications, a known methodology was applied in order to estimate the Global Tilted Irradiation for each valid location of the network. Once the Global Tilted Irradiation is estimated for a surface tilted with an angle equal to the local latitude angle, an estimation of the potential solar photovoltaic energy production was performed.

Key words: Global Hemispherical Irradiation, Measurements, Global Tilted Irradiation, Solar Photovoltaic.

1 Introduction

Typically, Global Horizontal Irradiance (GHI) is the most commonly component of solar irradiance to be measured since only a pyranometer and a data acquisition system are needed, making the system less expensive than those necessary to measure Diffuse Horizontal Irradiance (DHI) and Direct Normal Irradiance (DNI), requiring continuous tracking of the sun's apparent motion or several seasonal shadow band adjustments for standalone DHI measurement. In Portugal, there is an initiative from IPMA – Portuguese Institute for Sea and Atmosphere with a network of 89 locations measuring GHI across Continental Portugal for meteorological purposes [1] [2]. There is also an initiative from the University of Évora, in cooperation with several other entities, with 13 stations to measure DNI for solar concentration applications [3], the stations in this network typically also measure GHI and DHI.

These initiatives are important in order to create large and statistically significant datasets for purposes such as research and solar energy applications. When discussing statistical significance, Researchers propose different periods for solar radiation analysis which range from six to thirty years of data [4]. This kind of assessment is usually based on the supposition that the long-term average annual solar radiation from the past can provide an accurate estimation, without significant variability, for the availability of solar resources in the future [5] [6]. Discrepancies resulting from this assumption are often not considered or considered to be negligible in comparison to other uncertainties [7].

When analyzing solar radiation datasets, it is usual to find data gaps and thus it is necessary to apply a data gap filling procedure. There are several proposed procedures for the gap filling such as filling the missing days with the mean values of the available days of the same month, which may result in inaccurate estimates, depending on the number of missing days [9]. Other methods consist on a linear interpolation for gaps up to three hours, filling the gap with data for the same period from past years or correlation with data from a neighboring station.

This study takes into consideration the work previously developed in [1] [2] and presents the application of a well-known method [10] [11], to obtain the Global Tilted Irradiation (GTI) for a flat surface with a tilt angle equal to the latitude in order to optimize the annual intersection of solar radiation on that surface and estimate the energy production of a typical photovoltaic module. Usually, for an estimation of this kind to be accurate one should, at least, use hourly solar radiation data and hourly average air temperature in order to simulate the hourly photovoltaic energy production, taking into consideration the thermal effect on the reduction of photovoltaic energy production. Nevertheless, it is possible estimate the GTI with basis on Hemispherical Insolation values and still perform a rough estimation of the energy produced by a typical solar photovoltaic panel [10] [11].

2 Experimental Data and Data Quality

The data analyzed in this study results from studies previously performed with data from IPMA's network [1] [2]. These studies yielded as results monthly and yearly average values of GHI for continental Portugal, which will be used in the method described in Section 3.

The data from IPMA's network is recorded with secondary standard pyranometers according to ISO specifications, which are considered the best quality instruments for this purpose [1] [2].
Regarding data quality, the concerns are the same as stated in previous studies, the authors do not have accurate information about the actual proper operation of the instruments, thus the measurements could be affected by problems such as lack of calibration or malfunction and possible data acquisition failures [1] [2]. An attempt of performing a quality check on the data was performed for Évora, comparing a station from IPMA's network with one station from the University of Évora whose operation and maintenance is known to be good [1] [2]. The comparative data analysis performed for Évora, considering a well-maintained station from the University of Évora and a station from IPMA's network showed a good data correlation with an R^2=0.98 and m=1.0067, therefore it is assumed the quality of data measured by IPMA's stations is acceptable [1] [2].

3 Methodology

In order to obtain reliable GHI estimations, in the previous studies a quality data analysis and gap filling procedure was performed over IPMA's data, from which the average monthly GHI availability values used in this study were obtained [1] [2].
Then, a well-known methodology was used in order to estimate GTI on surfaces tilted to the local latitude angle, in order to optimize the annual solar radiation interception and consequently the photovoltaic energy production [10]. The methodology applied consisted in the determination of:

1. The average GHI monthly availability (kWh/m^2) values obtained in [1] [2] were divided by the number of days of each month and converted from kWh/m^2 to MJ/m^2 in order to obtain the monthly daily mean hemispherical insolation ($\overline{H}_h$).

2. Extraterrestrial radiation, H_0, was determined for the central day of each month [10]:

$$H_0 = \frac{T}{\pi} I_{o,n} \left[1 + 0.033 \cos\left(\frac{2\pi n}{365.25}\right)\right] \cos\lambda \cos\delta \left(\sin\omega_s - \omega_s \cos\omega_s\right) \tag{1}$$

with T= length of day in seconds; $I_{o,n}$=1366W/m^2 = solar constant; n= Julian day; λ=geographic latitude; ω_s=arccos$[-\tan\lambda\tan\delta]$ = sunset hour angle and $\delta = 23.45 \sin\left[\frac{360}{365}(284 + n)\right]$ = solar declination [10]

3. Clearness Index [10]:

$$\overline{K}_h = \frac{\overline{H}_h}{H_0} \tag{2}$$

4. Monthly average daily diffuse insolation ($\overline{H}_d$) on an horizontal surface [10]:

$$\overline{H}_d = \overline{H}_h \left[0.775 + 0.347\left(\omega_s - \frac{\pi}{2}\right) - \left[0.505 + 0.261\left(\omega_s - \frac{\pi}{2}\right)\cos[2(\overline{K}_h - 0.9)]\right]\right] \quad (3)$$

5. Monthly average daily insolation collected by a surface tilted at the local latitude angle ($\overline{H}_{col}$) [11]:

$$\overline{H}_{col} = \overline{H}_h\left(R_h - R_d\frac{\overline{H}_d}{\overline{H}_h}\right) \quad (4)$$

Being R_h [11]:

$$R_h = \frac{1}{d}\left\{\left(\frac{1}{\cos\phi} + \frac{1}{2}\rho(1-\cos\beta)\right)\left(a\sin\omega_c + \frac{b}{2}(\sin\omega_c\cos\omega_c + \omega_c)\right) - \frac{1}{2}\rho(1 - \cos\beta)\cos\omega_s\,(a\,\omega_c + b\,\sin\omega_c)\right\} \quad (5)$$

With $d = \sin\omega_s - \omega_s\cos\omega_s$; a=0.409+0.5016 sin($\omega_s$-1.047); b=0.6609-0.4767 sin (ω_s-1.047); $\omega_c = \min\left(\omega_s, \frac{\pi}{2}\right)$=sunrise and sunset hour angle; ρ=ground albedo [11]

And R_d [11]:

$$R_d = \frac{1}{d}\left\{\left(\frac{1}{\cos\phi} - \frac{1}{2}(1+\cos\beta)\right)\sin\omega_c + \frac{1}{2}(1+\cos\beta)\ \omega_c\cos\omega_s\right\} \quad (6)$$

4 Results

With the results obtained from the described methodology, the monthly averages of daily insolation collected by a flat surface tilted with and angle equal to the local latitude were processed in order to obtain the annual average GTI availability for each valid location of the network. With these results, it is possible to create a map of yearly average GTI availability in Portugal (Figure 1.a).
The GTI yearly average availability shows a similar pattern as that of the GHI yearly average availability obtained in [1] [2], GTI availability tends to be higher on the South mainly due to the number of hour of sun available in the Southern region of Portugal, it also increases from West to East, especially in the North and Center zones most probably due to the frequent formation of fogs in seaside (because of earth-sea interactions) [1] [2]. The GTI availability ranges from 1638 kWh/m^2/year to 2251 kWh/m^2/year.

Figure 1.b shows the estimated photovoltaic production yielded by a chosen module, in this case the OPEN 2XX-PM60 G2 from Open Renewables, a Portuguese manufacturer, with an efficiency of 16.4% and an area of 1.64m^2 [12]. A Performance Ratio (PR) was applied, using a typical value of 85%, considering 15% losses of the system due to cable losses, conversion losses, soiling on the photovoltaic module and heat losses. The average annual energy production estimated by a single photovoltaic module, with the referred considerations, ranges from 374 kWh to 514 kWh.

For an accurate estimation of the photovoltaic energy production, the data computation should be performed on an hourly basis, or less, using solar radiation and mean air temperature data as inputs, however the mean air temperature data was not available at the time and therefore the referred methodology in section 3 was applied in order to obtain rough estimations.

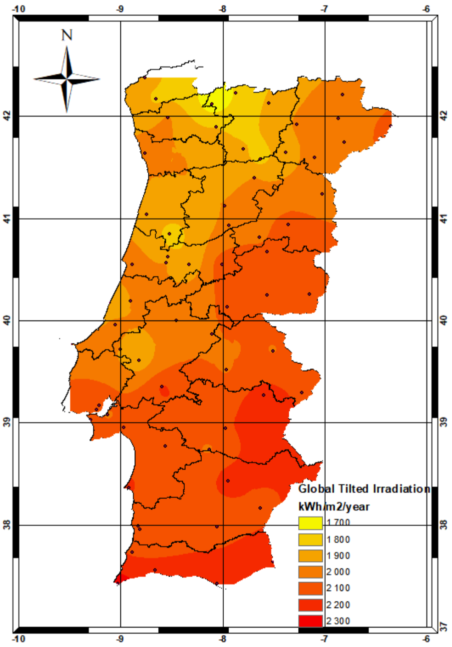

Figure 1.a. Average GTI annual availability for a tilt angle equal to the local latitude angle (kWh/m^2/year).

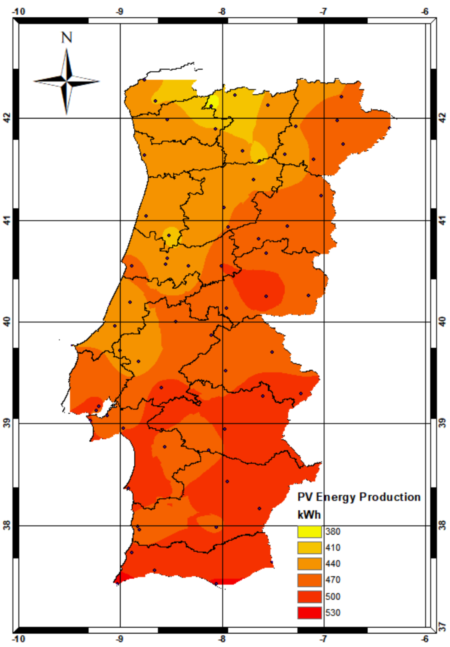

Figure 1.b. Average annual energy production by the chosen phovoltaic module

5 Conclusions

With basis on the GHI availability obtained in previous works [1] [2] it was possible to obtain a rough estimation of the yearly GTI average availability in Portugal, for surfaces with a tilt angle equal to the local latitude angle, optimizing yearly solar radiation interception.

For this study, taking into consideration the available data, the main objective was to perform a rough estimation of GTI in Portugal and a rough estimation of a PV module energy production. In the future a more accurate simulation and analysis will be performed.

In that future work, the conversion from GHI to GTI should be performed on an hourly basis in order to be used as an input as well as the average air temperature for a thorough photovoltaic simulation. Once the average air temperature is accessible the authors, will perform a thorough simulation in order to obtain a more accurate photovoltaic energy production with basis on hourly GTI and hourly average air temperature values. The presented work will serve for comparing the estimation of GTI yearly average values and PV yearly average energy production with a future and more accurate model.

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