Article – Smart Energy

Determination of Diffused Irradiation from Horizontal Global Irradiation - Study for the City of Curitiba

Muriele Bester de Souza[1*]
https://orcid.org/0000-0002-4510-5207

Édwin Augusto Tonolo[1]
https://orcid.org/0000-0002-8644-650X

Renata Lautert Yang[1]
https://orcid.org/0000-0002-1867-229X

Gerson Máximo Tiepolo[2]
https://orcid.org/0000-0002-0409-4484

Jair Urbanetz Junior[2]
https://orcid.org/0000-0001-9355-1730

[1] Universidade Tecnológica Federal do Paraná - Postgraduate Program in Energy Systems (PPGSE), Solar Energy Laboratory (LABENS), – Paraná, Curitiba, Brazil; [2] Universidade Tecnológica Federal do Paraná - Academic Department of Electrical Engineering (DAELT), Solar Energy Laboratory (LABENS).

* Correspondence: murielebester@gmail.com; Tel.: +55-41-996003310 (M. B. S.)

HIGHLIGHTS

- Review of solar radiation components.
- Acquisition of global irradiation data from INMET and UTFPR.
- Use of Liu and Jordan's and Page's method to calculate diffuse irradiation.
- Comparison with the results obtained in the Solar Energy Atlas - Paraná.

Abstract: Understanding the solar radiation values in the surface is important for the development of solar energy projects, obtaining through radiometers installed in certain places or publications as in solar energy atlases. Typically, solar or weather stations do not have sensors to measure diffuse irradiation due to high investment and the need for constant maintenance. This paper presents methods for the determination of diffuse irradiation from surface measured data of global horizontal irradiation in the city of Curitiba, obtained through pyranometers installed at the Federal University of Technology – Paraná (UTFPR) headquarters and from Curitiba-A807 National Institute of Meteorology (INMET) station. Two models are presented for the estimation of the monthly mean daily diffuse irradiation, based on the studies of Liu and Jordan (1960) and Page (1961). Finally, these data were compared with those presented by the Solar Energy Atlas - Paraná, verifying the percentage differences presented. It was observed that the model elaborated by Page presented better results in the diffuse radiation estimates when compared to the values

presented by the Paraná Atlas, with an average variation of -1.39% and -1.55%, for data from INMET and UTFPR respectively.

Keywords: Diffuse Irradiation, estimate, global irradiation, solar energy.

INTRODUCTION

Solar energy is not a renewable source of energy but an inexhaustible source of energy [1]. The publication by INPE (National Institute for Space Research) of the Brazilian Solar Energy Atlas 2nd edition (2017) shows that Brazil has great solar potential, where even in the less sunny place it is viable to install photovoltaic solar energy systems.

In December 2017, the first Solar Energy Atlas - Paraná was published, whose project was the result of a partnership between UTFPR, INPE, Itaipu Binational and the Itaipu Technological Park (PTI). However, during the project, it was perceived a difficulty in validating the data estimated by the BRASIL-SR model with the surface's collected data, since the state of Paraná does not have its own solarimetric grid, needing this information to improve it and develop new research in this sector, whether thermosolar or photovoltaic systems.

Each system has its way of operation: thermals depend exclusively on direct solar irradiance, whereas photovoltaics uses all available irradiance, either on a fixed inclined plane or through solar trackers [2]. In Figure 1 is presented a basic representation of the solar radiation components, according to the Solar Energy Atlas - Paraná [3].

According to Pinho and Galdino [4] the radiation components are described as:

Extraterrestrial irradiance: Solar irradiance that reaches the top of the Earth's atmospheric layer.

Beam irradiation: Solar irradiation that focus directly on the surface without any influence.

Diffuse irradiation: Solar irradiation that reaches the surface after being scattered throughout the earth's atmosphere.

Reflected irradiation (albedo): irradiation reflected by the surrounding environment (soil, vegetation, obstacles, rocky terrain, etc.).

Global irradiation: amount of irradiation resulting from the sum of direct, diffuse and albedo solar irradiations.
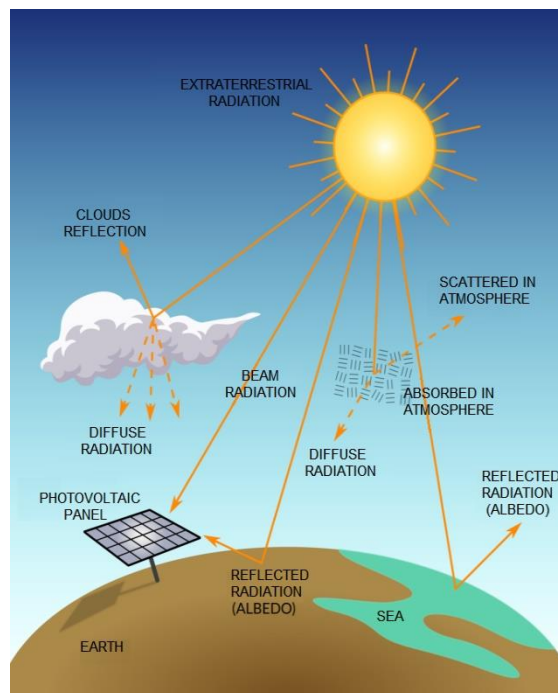
Figure 1. Representation of Solar Radiation Components.

For photovoltaic use, the most interesting is the global horizontal irradiation, which quantifies the radiation received by a horizontal flat surface. On cloudy days, the main portion is from the horizontal diffuse irradiation, whereas on clear days direct irradiation prevails [5].

Currently at INMET's climatological stations, only the horizontal global component is collected. The accuracy and quality of solar radiation data collected by equipment is very important and depends on the manufacturer's recommended installation, operation, and maintenance, and should follow the International Organization for Standardization (ISO) and World Meteorological Organization (WMO) that establish ratings and specifications for solar irradiance measurement [1].

Due to the different characteristics of the components and the difficulty of obtaining the diffuse fraction out of the measured data, this work aims to determine the diffuse irradiation from global horizontal surface measured irradiation in the city of Curitiba, using the models studied by Liu and Jordan [6] and Page [7], and compare the data estimated by these models with the data presented in the Solar Energy Atlas - Paraná.

MATERIAL AND METHODS

Global radiation is monitored by two KIPP & ZONEN - CMP3 Second Class thermoelectric pyranometers [8], as shown in Figure 2 and positioned in a horizontal plane. The data obtained are from 12 months, from June 2017 to May 2018 and were acquired from INMET's pyranometer installed at Curitiba-A807 Station [9], Curitiba - PR, with latitude of 25º26.922' S and longitude of 49º13.836' W. The other pyranometer is located at UTFPR, Curitiba central campus, located at 3165 Sete de Setembro Avenue, with latitude 25º26.352' S and longitude 49º16.176' W.

Figure 2. Pyranometer CMP3.

The data collected from the horizontal global component, both by the weather station and by the UTFPR, are in solar irradiance (W/m²), stored hourly, therefore, they are also hourly solar irradiation data (Wh/m²). To estimate diffuse irradiation, assumptions and calculations presented in this section are required.

Extraterrestrial solar radiation on a horizontal surface is obtained, according to Macagnan [10], by Equation 1:

$$Ion = Isc. Eo \qquad (1)$$

where, Ion is the extraterrestrial irradiance, Isc is the solar constant equal to 1367 W/m² and Eo is the earth-orbit eccentricity correction factor, described in Equation 2:

$$Eo = Isc \left(1 + 0,033. \cos \frac{360. n}{365}\right) \qquad (2)$$

Where n is the day in the Julian calendar, ranging from 1 (January 1) to 365 (December 31), shown in Table 1.

Table 1. Standard average day of the month.

Month	n for i:th Day of the month	For the average day of the month		
		Date	n, day of the year	δ, declination (°)
January	i	17	17	-20.9
February	31+i	16	47	-13
March	59+i	16	75	-2.4
April	90+i	15	105	9.4
May	120+i	15	135	18.8
June	151+i	11	162	23.1
July	181+i	17	198	21.2
August	212+i	16	228	13.5
September	243+i	15	258	2.2
October	273+i	15	288	-9.6
November	304+i	14	318	-18.9
December	334+i	10	344	-23

Data obtained in [10].

By obtaining the solar irradiation data on the terrestrial surface through the INMET and UTFPR pyranometers, and from the extraterrestrial irradiation calculation, it is obtained the values of the atmospheric transmissivity index (Kt), which is defined as the ratio between the solar radiation on the earth's surface (H) to the solar radiation reaching the top of the

atmosphere (Ho). It varies according to the amount of clouds and aerosols in the atmosphere, and there may be increase or decrease of direct or diffuse components of solar radiation that reach the surface [11]. Kt is defined by Equation 3:

$$Kt = \frac{H}{Ho} \tag{3}$$

To calculate monthly mean daily horizontal extraterrestrial irradiation, the average day of the year is used, which is the day of the year when daily extraterrestrial radiation is almost equal to the monthly average value. It was noted that the 16th day of each month can lead to minor errors in Ho, especially for June and December, which are the solstices. The recommended days for each month are given in Table 1. It can be estimated Ho from Equation 4:

$$Ho = \frac{24}{\pi} . \, Isc. \, Eo[\left(\frac{\pi}{180}\right). \, \omega s. \, (\sin(\delta). \sin(\varphi)) + (\cos(\delta). \cos(\varphi). \sin(\omega s))] \tag{4}$$

where, ωs is the angle of the sun's rise, in degrees, and can be obtained from Equation 5:

$$\omega s = \cos^{-1}(-tg(\varphi). \, tg(\delta)) \tag{5}$$

where φ is the local latitude, in degrees and δ is the solar declination, in degrees, and is calculated from Equation 6

$$\delta = 23,45°. \sin(360 \, \frac{284 + n}{365}) \tag{6}$$

After determining the Kt index, it is estimated the variation of the daily diffuse fraction Kd, which is the ratio between diffuse irradiation Hd and global horizontal irradiation in the surface H, and is defined by the Equation 7:

$$Kd = \frac{Hd}{H} \tag{7}$$

The first method used to estimate the monthly mean daily diffuse solar irradiation on horizontal surface was Liu and Jordan's [6], is defined by Equation 8 and has as its parameter the Kt index.

$$\frac{Hd}{H} = 1,39 - 4,027. \, Kt + 5,531. \, Kt^2 - 3,108. \, Kt^3 \tag{8}$$

The second method used to estimate the monthly mean daily diffuse solar irradiation was Page's [7] and is defined by Equation 9, also as a function of the Kt index:

$$\frac{Hd}{H} = 1,00 - 1,13. \, Kt \tag{9}$$

RESULTS

Through the data obtained by the INMET and UTFPR's pyranometers, in the 12-month period (June 2017 to May 2018), it can be seen that these values, compared to the Solar Energy Atlas - Paraná, presented values close to the Atlas, which has estimates of solar radiation based on 17 years of satellite data (1999 to 2015).

Table 2 and Table 3 show the months of the year analyzed, the calculated values of transmissivity indices (Kt) and diffuse fraction (Kd) for INMET and UTFPR.

Measured horizontal global irradiation and estimated horizontal diffuse irradiation according to the Liu - Jordan and Page methods, respectively, were also presented. Finally, the percentage variation between the diffuse irradiation values estimated by the models and those presented by the Solar Energy Atlas - Paraná is presented.

The indices Kt and Kd are dimensionless values, since they represent the fraction of the components that arrive at surface, being the global and diffuse irradiations represented in W.h/m².day.

The methods for determination of the diffuse irradiation component chosen from Liu and Jordan (Table 2) and Page (Table 3) presented expected diffuse irradiation data when

compared to those presented by the Atlas, where it is assumed that the models are viable to estimate it.

Table 2. Comparison of data with calculated Kd by the Liu and Jordan's method.

Month	Year	Kt INMET	kd INMET	Kt UTFPR	kd UTFPR	Global INMET Wh/m².day	Global UTFPR Wh/m².day	Global Atlas Wh/m².day	Diffuse INMET calculated Wh/m².day	Diffuse UTFPR calculated Wh/m².day	Diffuse Atlas Wh/m².day	Percentage Variation INMET-Atlas	Percentage Variation UTFPR-Atlas
June	2017	0.491	0.378	0.505	0.367	2900	2979	2755	1096	1093	1268	-13.55%	-13.80%
July	2017	0.554	0.328	0.590	0.301	3430	3654	2903	1126	1100	1301	-13.45%	-15.43%
Aug.	2017	0.450	0.414	0.480	0.387	3340	3561	3884	1383	1380	1466	-5.63%	-5.90%
Sep.	2017	0.532	0.345	0.476	0.391	4830	4320	3844	1665	1689	1898	-12.27%	-11.01%
Oct.	2017	0.379	0.489	0.397	0.469	4010	4200	4348	1962	1969	2344	-16.28%	-15.98%
Nov.	2017	0.476	0.391	0.473	0.394	5510	5480	5232	2156	2157	2638	-18.25%	-18.23%
Dec.	2017	0.396	0.470	0.396	0.470	4740	4740	5558	2227	2227	2792	-20.24%	-20.24%
Jan.	2018	0.410	0.455	0.418	0.446	4850	4950	5258	2205	2207	2670	-17.42%	-17.35%
Feb.	2018	0.452	0.413	0.434	0.430	5000	4810	5187	2066	2066	2469	-16.33%	-16.31%
Mar.	2018	0.428	0.436	0.434	0.430	4200	4260	4551	1830	1831	2197	-16.68%	-16.67%
Apr.	2018	0.574	0.313	0.570	0.316	4660	4630	3778	1458	1462	1828	-20.22%	-20.03%
May	2018	0.530	0.347	0.541	0.338	3510	3580	3031	1217	1211	1458	-16.56%	-16.91%
MEAN		0,47	0.40	0.48	0.39	4248	4264	4194	1699	1699	2027	-15.57%	-15.66%

Comparison between the Solar Energy Atlas - Paraná with those obtained by INMET station and UTFPR.

Table 3. Comparison of data with calculated Kd by the Page's method.

Month	Year	Kt INMET	kd INMET	Kt UTFPR	kd UTFPR	Global INMET Wh/m².day	Global UTFPR Wh/m².day	Global Atlas Wh/m².day	Diffuse INMET calculated Wh/m².day	Diffuse UTFPR calculated Wh/m².day	Diffuse Atlas Wh/m².day	Percentage Variation INMET-Atlas	Percentage Variation UTFPR-Atlas
June	2017	0.491	0.445	0.505	0.430	2900	2979	2755	1290	1280	1268	1.74%	0.95%
July	2017	0.554	0.374	0.590	0.333	3430	3654	2903	1283	1218	1301	-1.35%	-6.38%
Aug.	2017	0.450	0.491	0.480	0.457	3340	3561	3884	1640	1628	1466	11.85%	11.07%
Sep.	2017	0.532	0.398	0.476	0.462	4830	4320	3844	1924	1995	1898	1.37%	5.13%
Oct.	2017	0.379	0.572	0.397	0.552	4010	4200	4348	2294	2317	2344	-2.14%	-1.14%
Nov.	2017	0.476	0.462	0.473	0.465	5510	5480	5232	2548	2550	2638	-3.42%	-3.33%
Dec.	2017	0.396	0.553	0.396	0.553	4740	4740	5558	2620	2620	2792	-6.17%	-6.17%
Jan.	2018	0.410	0.537	0.418	0.527	4850	4950	5258	2604	2610	2670	-2.48%	-2.24%
Feb.	2018	0.452	0.490	0.434	0.509	5000	4810	5187	2448	2449	2469	-0.83%	-0.82%
Mar.	2018	0.428	0.516	0.434	0.509	4200	4260	4551	2168	2170	2197	-1.32%	-1.25%
Apr.	2018	0.574	0.351	0.570	0.355	4660	4630	3778	1637	1646	1828	-10.46%	-9.98%
May	2018	0.530	0.401	0.541	0.389	3510	3580	3031	1408	1393	1458	-3.45%	-4.45%
MEAN		0.47	0.47	0.48	0.46	4248	4264	4194	1989	1990	2027	-1.39%	-1.55%

Comparison between the Solar Energy Atlas - Paraná with those obtained by INMET station and UTFPR.

DISCUSSION

It was found that the mean variation between diffuse irradiation obtained by the Liu and Jordan method for UTFPR in relation to Atlas is -16%, the same percentage found among the values obtained for INMET in relation to Atlas. This shows that the data obtained by the studied sites are very similar and have a considerable average variation in relation to the Atlas data, which was the reference used.

However, for the Page method, the average variation of diffuse irradiation presented between the values obtained for UTFPR in relation to Atlas was -1.55%, while for INMET the variation was -1.39%. These results show that the studied methods presented values very close to those found in the Atlas in the analyzed period.

Studies such as Crotti and Rampinelli [13] show that the lower the value of the Kt index, the higher the value of the Kd index, which can be observed in Figure 3 and Figure 4. This shows the convergence of the studies to different locations analyzed, proving the validation of the used methods.
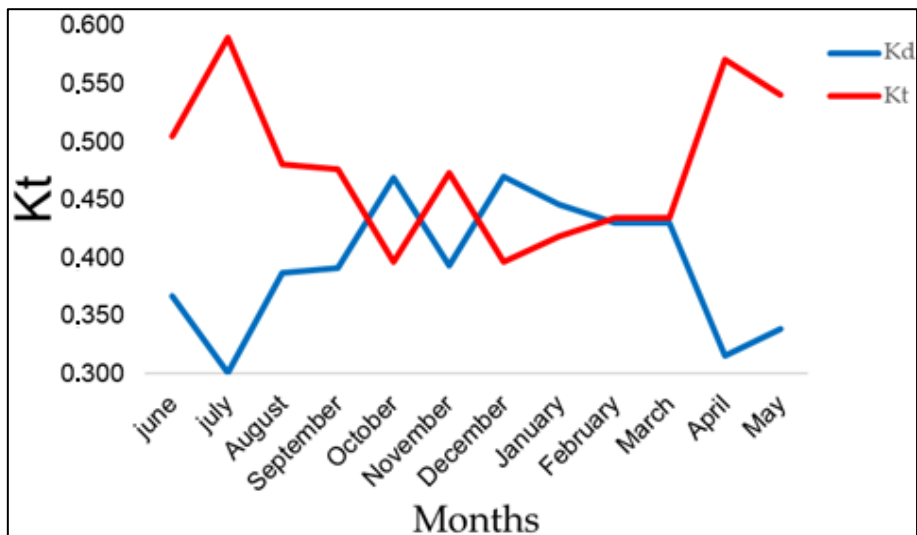

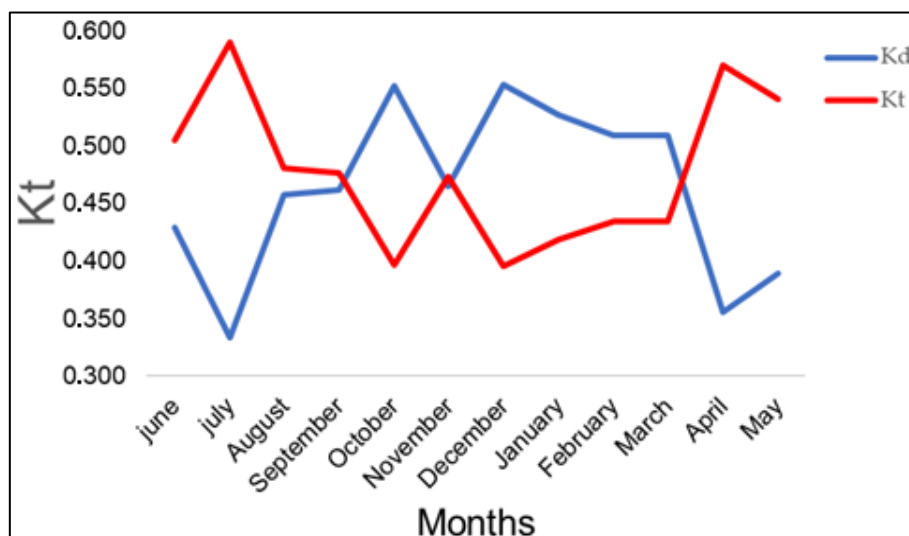**Figure 3.** Comparison between Kt and Kd (Liu e Jordan's method).

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Figure 4. Comparison between Kt and Kd (Page's method).

CONCLUSION

This work presented analyzes for models in order to estimate the average daily diffuse irradiation by choosing Liu and Jordan's and Page's models. With the results presented in Tables 2 and 3, there was less variation between the data when calculated by the Page's method. This does not mean that the Liu and Jordan's method is less reliable, because it must be taken into account that the studied period is short compared to the values presented in the Solar Energy Atlas - Paraná in which a comprehensive historical data, between 1999 and 2015, was used.

It can also be seen from the comparisons that the data measured by the INMET-Curitiba Station and the UTFPR, of horizontal global irradiation are similar.

It was found that in the periods between April and August (autumn and winter seasons) the proportion of diffuse irradiation was smaller than in the other months of the year, characterized by less cloudiness and sunnier days compared to other periods of the year. This information is confirmed by the maps presented in the Solar Energy Atlas - Paraná, where seasonal daily averages of diffuse irradiation are shown.

Finally, to know which of these models presents the best estimate of diffuse irradiation, it would be ideal to obtain the measured values of this component, which is intended to be accomplished in a next step of this research.

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