Estimation of Solar Resource by means of spatial interpolation

Samira Fontes Domingos[1], Rodrigo Andrade da Silveira[1], Wallace do Couto Boaventura[1] and Luís Guilherme Monteiro Oliveira[2]

[1] Graduate Program in Electrical Engineering - Federal University of Minas Gerais - Av. Antônio Carlos 6627, Pampulha, 31270-901, Belo Horizonte, MG, Brazil.

[2] Energy Engineering Department - Pontifical Catholic University of Minas Gerais - Av. Dom José Gaspar 500, Coração Eucarístico, 30535-060, Belo Horizonte, MG, Brazil.

Abstract

Data from three weather stations is used to estimate the Global irradiance by means of data interpolation which are then compared with the solar resource estimated from nearby PV system. This numerical interpolation is be able to estimate the Global irradiance in the area englobing the weather station. The proposed method can be used to make a first analysis of Global irradiance on sites without Global irradiance measurements. That evaluation was conducted for Brazil, on Minas Gerais state with a Tropical weather with dry season.

Keywords: Estimation of solar resource, photovoltaic, solar energy, interpolation.

1. Introduction

The knowledge of solar radiation causes direct and positive impacts: from negotiations in electric energy bid, to the leveling of load demand curves, even reducing the production from other power sources such as thermal and hydraulic.
"Photovoltaic (PV) generation has a stochastic nature and is related to weather variables such as temperature, water vapor, aerosol levels, and in particular, cloud movements." (Yang, et al., 2017)
Nowadays, there are consolidated complex methods to estimate the solar resource for locations that do not have Global Irradiance measurement. They are complex because they use heavy numerical studies and many climatic variables to better characterize the region microclimate.

In this work, a methodology is proposed to predict Global irradiance where sensors are not available. The predictions are very simple to obtain, since they are numerical interpolations and do not use climatic variables. Different weights are used for the data from the weather stations depending on their distance to the site of interest. The major contribution of this paper is the demonstration that with free Global irradiance data from public weather station next to a site of interest it is possible to improve the accuracy of publicly available Global irradiance estimate. Moreover, be demonstrate that it can be achieved without requiring any weather information.

2. Spatial variability of solar resource

The variability of Global irradiance at ground level is dependent on the local microclimate and its data reports are dependent on the averaging timescale used Badescu 2008 APUD (Coimbra, et al., 2013). Besides, there are several factors affecting it, like gases, aerosols, solar position and cloud cover.

There are some studies about the precision of estimate when the weather stations are far from the site of interest. For weather stations farther than 30 km, assessments based on satellite techniques are preferable (Ruiz-Arias, et al., 2015). For a regularly spaced network, the distance among the stations is estimated to be 50 km (Perez, et al., 1997).

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The Brazilian Atlas of Solar Energy (Pereira, et al., 2017) suggests then that the use of radiative transfer is a better option when the distance from the stations are longer than 30km, since the error of data interpolation is lower.

There are some works for interpolation, like these show in the next.

(Grossi Gallegos & Lopardo, 1988) suggest that for an error lower than 8,5% and the required confidence level of 90%, it may be seen that the extrapolation of monthly averages Global irradiance could be extended up to 150 km from the measuring site and up to 225 km for an error lower than 10%. In this context, this work proposes a methodology to estimate solar resource using interpolated data from ground weather stations resulting in lower errors.

"Angström–Prescott model consists in using the mean values (generic) of the site-calibrated A–P parameters to compute the global solar radiation at any location from the number of bright sunshine hours." (Meher, et al., 2015) Compared the interpolation method of the A–P regression parameters with the conventional method (generic A–P parameters) and showed that they have similar results.

The study of (Junyu, et al., 2019) compared interpolation weather data and NASA North American Land Data Assimilation System Phase Two (NLDAS2) weather data used in SWAT application at a large-scale watershed—the Upper Mississippi River Basin (UMRB) and as result the SWAT model underestimated stream flow in the UMRB due to the overestimation of evapotranspiration in the scenario of NLDAS2-SWAT.

Geostatistical interpolation and stochastic simulation approaches are compared for (Jeonga, et al., 2017) and the comparison is only based on the performances of two approaches because they have different application constraints and algorithms to each other and the end suggests a guideline to select an appropriate simulation approach.

(Lefevre M, 2002) demonstrates that "taking into account the latitudinal effects in the distance increases the accuracy in interpolation."

3. Characterization of weather stations and solar power plant

The weather station and the Solar Power Plant are in different cities, but all in the Minas Gerais state. Minas Gerais is a mountainous region, it is the second more populated state in Brazil and the fourth largest. Belo Horizonte city is the capital of the state and had 2.5 million of people in 2018 (IBGE, 2018).

In Brazil, the INMET (National Institute of Meteorology) manage more than 400 weather stations (equipped with pyranometers sensors) taking measurements of Global irradiance, as shown in Figure 1. However, there is the need to estimate the solar resource in places apart from the weather stations, because the stations are distant. The INMET's data are free, with easy access and the data of Global irradiance is one measurement per hour.

Fig. 1: Localization of weather stations on Brazil. Source: (INMET, 2019a)

The triangle inside the Figure 2 is about 50 km each side, and is close to Belo Horizonte city, detailed in Figure 3.

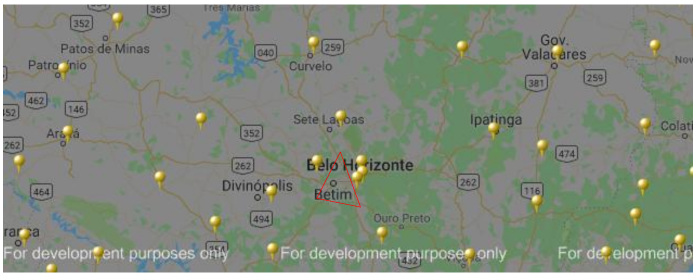

Fig. 2: Localization of weather stations on Minas Gerais State. Source: (INMET, 2019a)

The Figure 3 shows the localization of three automatics weather station from INMET on the vertex of the triangle and the Solar Power Plant, taken as the site of interest for validation purposes, is inside the triangle.

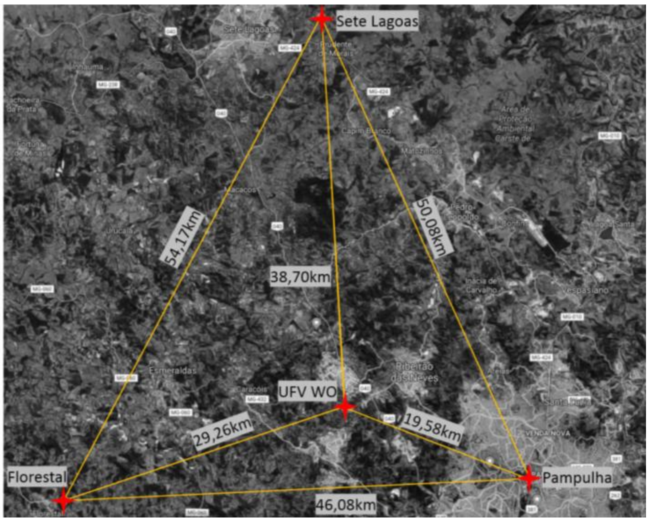

Fig. 3: Localization of three weather stations and the UFV. Source: (Google, 2019)

The Table 1 shows details of three weather stations and the Mini PV system UFV WO.

Tab. 1: Details of weathers stations

Name	**Pampulha's weather station**	**Sete Lagoas's weather station**	**Florestal's weather station**	**PV system UFV WO**
Ofitial Name	Pampulha – A521	Sete Lagoas-A569	Florestal – A535	UFV Wagner Oliveira
Coordinates (Lat; Long)	-19.883945º; -43.969397º	-19.455288º; -44.173380º	-19.885398º; -44.416883º	-19.802°; -44.151°
Altitude [m]	854	719	754	-
Installed Power	-	-	-	5,67 kWp

Data Source: (INMET, 2019a)**,** (IMAX Energia, 2019)

The Pampulha's weather station is in a high-density urban region on Belo Horizonte downtown, the Sete Lagoas's weather station is on Sete Lagoas downtown, and the Florestal's weather station is located on Florestal's downtown.

The Mini Solar Power Plant UFV WO is located on Ribeirão das Neves's district (close to the capital). The power measurement is recorded in one per 5 minutes basis and was converted in solar radiation and then calculated the mean value for 1 hour.

The weather stations have differences, like the terrains, which contribute to the formation of different microclimates. Figure 4 shows the global Global irradiance for those weather stations for a period of two days.

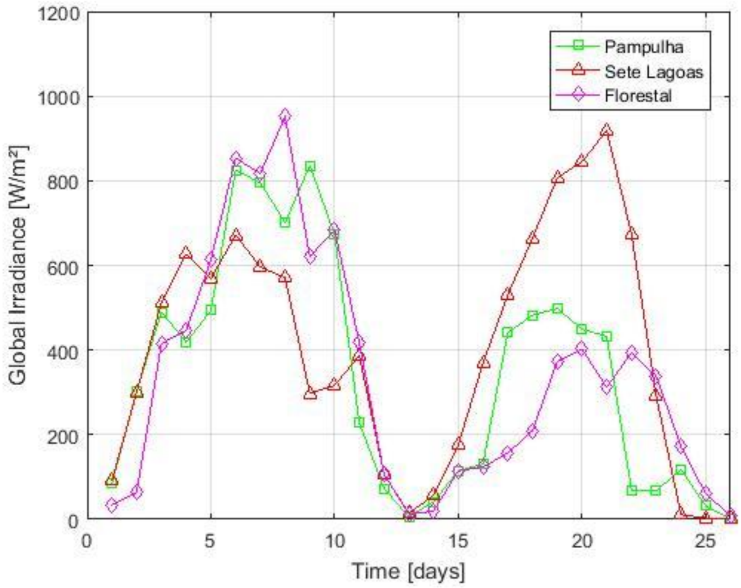

Fig. 4: Global Irradiance for the three stations: Two days global irradiance. Data Source: (INMET, 2019a)**.**

Figure 5 presents the comparison among Pampulha and the others weather stations for fifty-one days. The weather stations have differences, like the terrains, which contribute to the formation of different microclimates. Figure 3 presents the comparison among Pampulha and the others weather stations for all days. Pampulha's weather station differs from the others, mainly due to the microclimates.

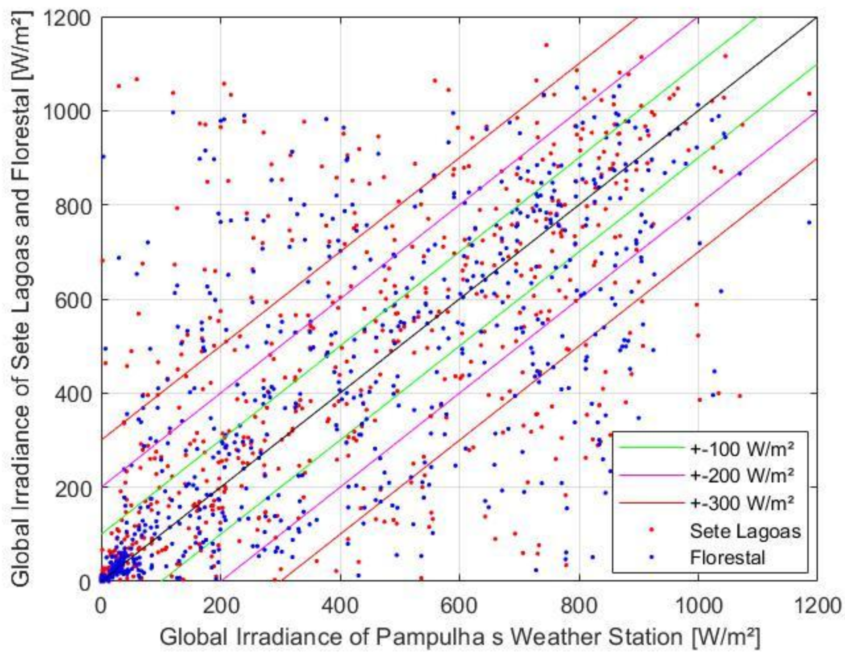

Fig. 5: Global Irradiation of the three stations: Comparison of weather stations. Data Source: (INMET, 2019a)**.**

The observation period was 05/02/2019 to 15/04/2019, 13 hour per day. Some days does not have measurement or has some error and were not considered. This data supported the simulations, done for fifty-one valid days.

In Brazil, up until March 20th is summertime and after is autumn, so March is the change of seasons. For a 30 years average, in Belo Horizonte, February has 206mm, March has 143mm and April has 45mm of accumulated rain. February and March have average temperature between 19 and 29 degrees and April between 17 and 28 degrees. (Climatempo, 2019)

4. Methodology

A spatial interpolation was applied with Global Irradiance data from the three weather stations from INMET using MATLAB. "The function returns the interpolated values on a refined grid formed by repeatedly halving the intervals k times in each dimension. This results in $2^{(k-1)}$interpolated points between sample values" (Math Works, 2019). In this work, k = 3 times and V is a 2x2 matrix with the weather stations Global irradiance values for each hour of the day. The result is a 9x9 matrix with the weather stations values on each corner and the interpolated data on the other positions.

For validation purposes, we chose to make the spatial interpolation at the location of an operating mini solar PV power plant call UFV WO. Therefore, the information of the power generation will be used to estimate the solar resource and these data will be compared with the data interpolation from INMET weather stations.

A study was carried out to find the relationship between the localization of the interpolated data selected and the localization (latitude and longitude) of PV system. For the 9x9 matrix, was selected the cell starting the stations data coordinates and proportionally was found the cell where is the PV system.

The basic parameters for UFV-WO are: 34.56 m2, 18 polycrystalline315 Wp CS6x-315p modules, 16.42 % efficiency, 5.67 kWp total power. The following parameters are monitored: alternating current voltage, current, power and energy at inverter output, continuous current voltage, current and power at the inverter input. The values at the inverter input, which are used for MPPT, are used to calculate the instantaneous power produced by the plant used for instantaneous irradiance estimation. It is worthy to note that the modules temperature is not considered and the estimation is done for horizontal plane.

The power measurement is recorded in one per 5 minutes basis. Upon conversion to irradiance, the result a mean value is calculate for a period of one hour to meet the INMET data.

To better estimate the module efficiency, a performance ratio – PR was calculated from the measurement data. It was based on plant production data referred to Standard Test Condition – STC. This calculation is done according to Nobre (2015). The following equations were used:

$$PR = \frac{Y_f}{Y_R} \quad \text{(eq. 1)}$$

$$Y_f = \frac{E_{AC}}{P_O} \quad \text{(eq. 2)}$$

$$Y_R = \frac{\sum_0^t G_{mod}}{G_O} \quad \text{(eq. 3)}$$

$$PR = \frac{\frac{E_{AC}}{P_O}}{\frac{\sum_0^t G_{mod}}{G_O}} \quad \text{(eq. 4)}$$

$$\sum_0^t G_{mod} = \frac{E_{AC} * G_O}{P_O * P_R} \quad \text{(eq. 5)}$$

Where:

PR: performance ratio,

Yf: final yield,

YR: reference yield,

EAC: energy output [kWh],

Po: CC power input to the inverter [W].

Go: STC irradiance [W/m²]

Gmod: irradiance at the module plane [W/m²]

Once the performance ratio was obtained, the module efficiency is estimated and an estimate value for the irradiance is produced (Souza & Aristone, 2016) apud (Treble, 1980) and (Overstraeten & Mertens, 1996) equation 6:

$$G = \frac{V_{mp}\, I_{mp}}{A\, \eta} \qquad \text{(eq. 6)}$$

η = Module's Efficiency [%]

V_{mp} = Module’s Voltage [V]

I_{mp} = Module’s current [A]

A= Module’s area [m²]

G = Global Irradiance [W/m²]

The PV system WO has 34.56m² formed with 18 modules of Poly-crystalline with 315 Wp, model CS6x-315P-Si of Canadian Solar and 16.42% of efficiency. The solar plant is 5.670kWp.

The power measurement is recorded in one per 5 minutes basis and was converted in solar radiation and then calculated the mean value for 1 hour.

The observation period for the two case was the same. It was among 05/02/2019 to 04/04/2019, 13 hour per day. Eight days does not have measurement or has some error and were not considered: 13,16,17,26/02 and 01,05,12,13/03. This data supported the simulations, done for Fifty-one valid days. For this work, just the Global irradiance was considerate. Others weather’s information like temperature, wind and altitude was not taken into consideration.

In Brazil, up until March 20th is summertime and after is autumn, so March is the change of seasons. For a 30 years average, in Belo Horizonte, February has 206mm, March has 143mm and April has 45mm of accumulated rain. February and March have average temperature between 19 and 29 degrees and April between 17 and 28 degrees. (Climatempo, 2019)

5. Results

The Histogram of the Figure 6 shows the frequency distribution of three weather stations for all valid days. It is worthy to note they have many common distributions, shown in dark purple. The dark purple chart columns, show 20% until 100W/m² and 50% until 400W/m².

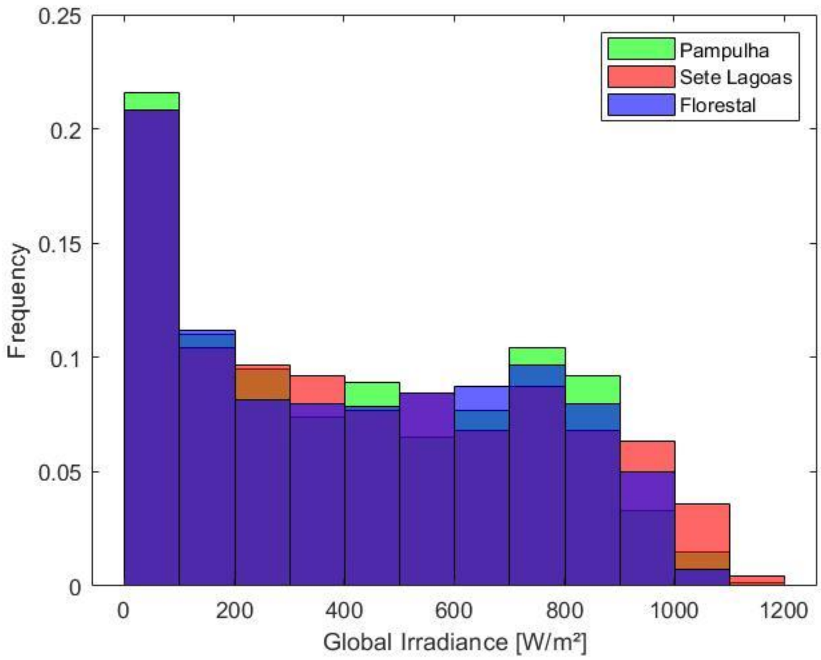

Fig. 6: Histogram with the frequency of occurrence to each Global irradiance zone for weather stations.

The Figure 7 shows the frequency distribution comparison between UFV WO and data interpolation results, shown reasonable agreement, shown in dark blue. The dark blue chart columns, show almost 20% until 100W/m² and 50% until 500W/m².

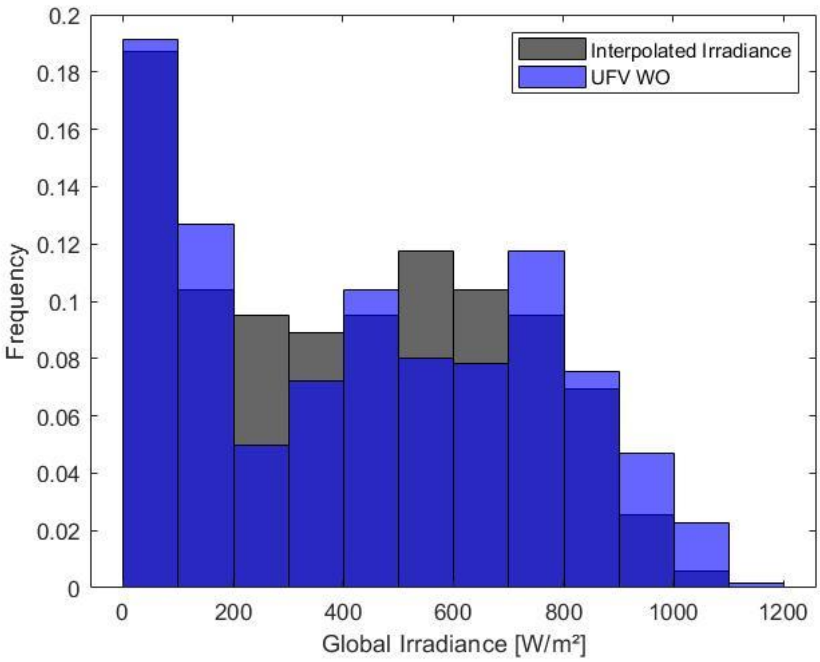

Fig. 7: Histogram with the frequency of occurrence to each Global irradiance zone for the power plant and interpolated data.

The interpolated data from the three weather stations uses a higher weight for Pampulha's data, since it is closer to UFV WO, benefitting the efficacy of spatial interpolation. Generally, the interpolated value it is close to the middle point among the three stations, but the behavior of WO value is a little different from the weather stations values. This can be attributed to the microclimate differences for these locations. The Figure 8 shows the Global irradiance of stations, WO and interpolated data results for two days. Its important to see how differents are the data among the stations. The clouds are different and then all the climate too.

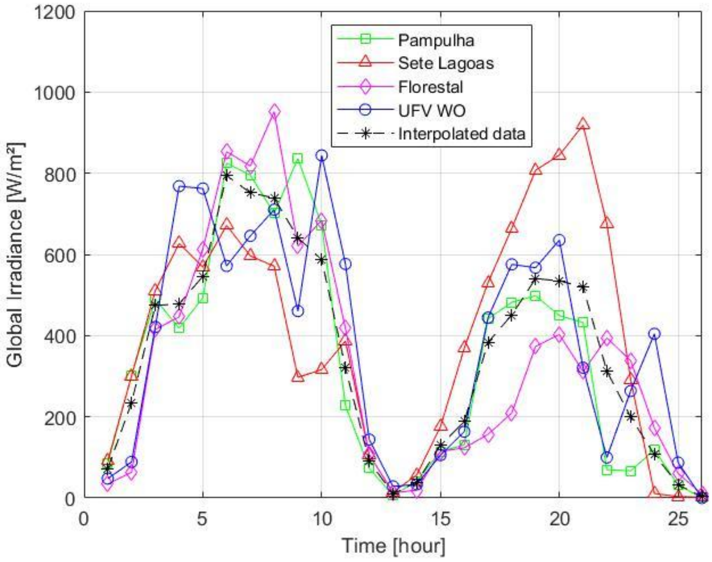

Fig. 8: Global Irradiance of three weather station, the PV Solar Power Plant and interpolated data results.
Data Source: (INMET, 2019a)**.**

The Figure 9 shows the comparison between the UFV WO and the interpolated data, showing the bands of error for 8.44% error for Global Irradiance, which is on average of 100 W/m², mostly of the data, and 25.31% error for 300W/m². This Figure shows that the difference between the Interpolated data and measurement data is mostly less then 100W/m

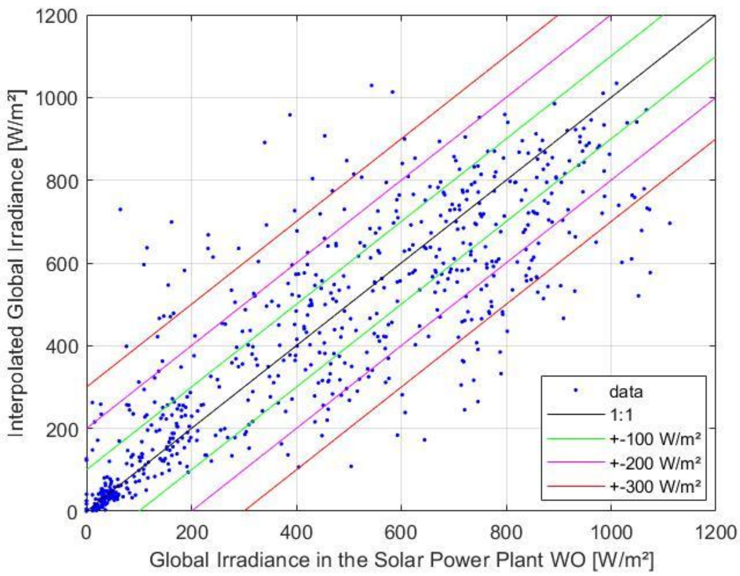

Fig 9. Comparison between the UFV WO and interpolated data for fit linear.

Using data from Figure 9, Figure 10 shows the linear fit between Interpolation and WO.

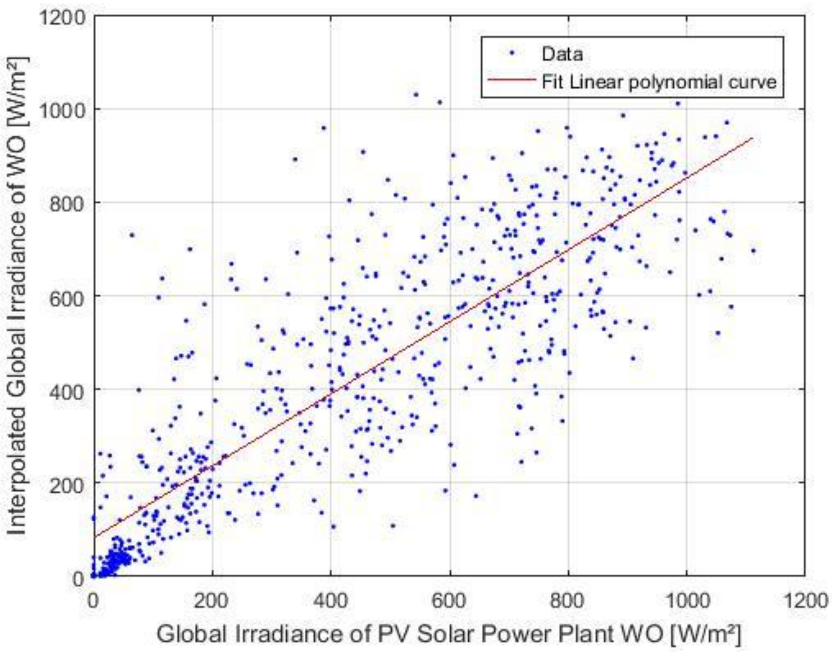

Fig 10. Comparison between the UFV WO and interpolated data for fit linear.

Figure 11 shows the Probability Density Function (PDF) giving a probability distribution for Global irradiance (with Normal distribution), allowing to calculate the Cumulative Distribution Function (CDF), in Figure 12.

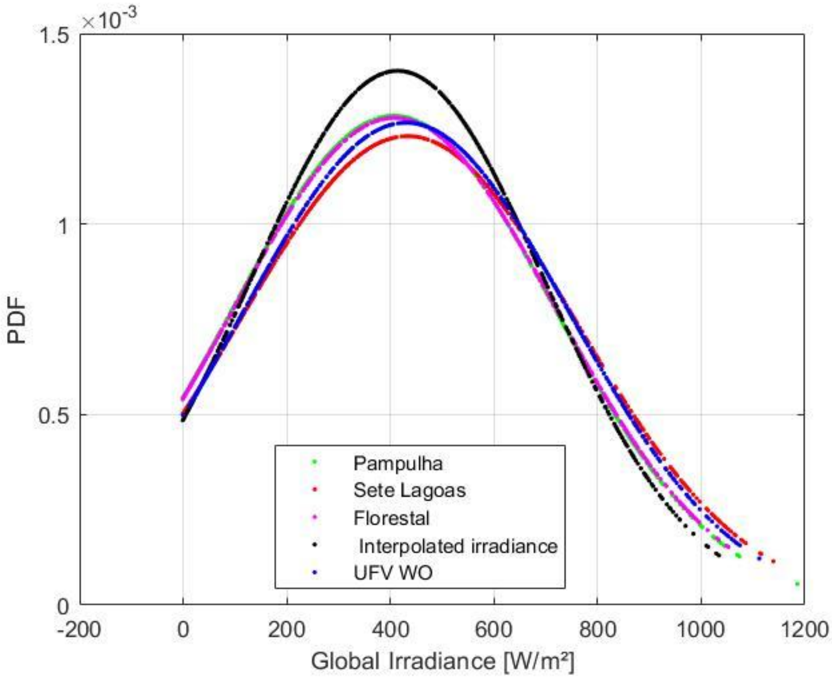

Fig.11: Stations, Power plant and interpolation: PDF.

In the Figure 12, the interpolated data is highest between 200 and 600 W/m². In this PDF graphic, this means that between these irradiances, the interpolated data has a higher probability to appear. The Table 2 show the statistics error for this case.

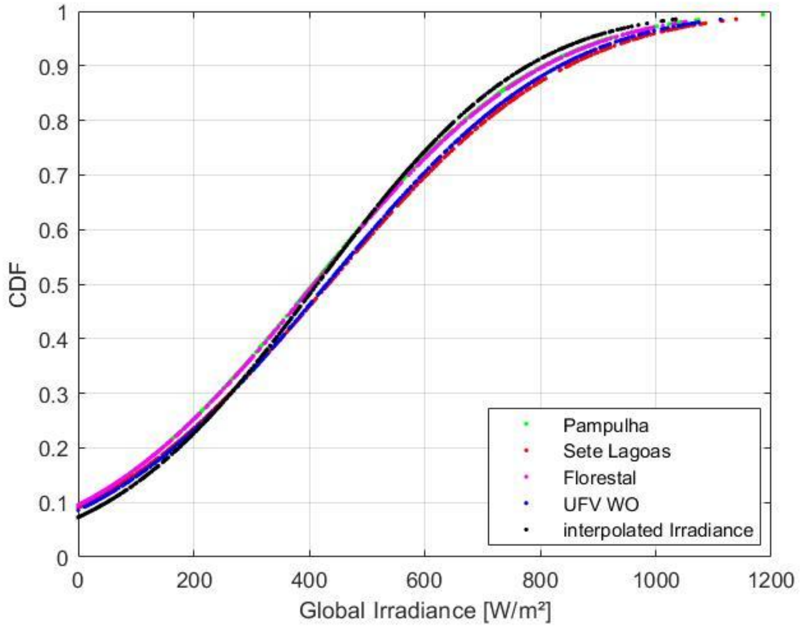

Fig.12: Stations, Power plant and interpolation: CDF.

6. Error statistics

Error statistics are common to evaluate a new forecast method. Each error statistics has a different interpretation of the method and turn possible to evaluate clearly. The errors statistics selected are show: Mean Absolute Error (MAE), Mean Bias Error (MBE) - most used bias - and Root Mean Square Error (RMSE) (Carlos F.M. Coimbra, 2013)

The adhesion test KSI Test (Kolmogorov-Smirnov Test) quantify the ability of a model to reproduce observed frequency distributions. For the result h = 1, it rejects the null hypothesis at the 5% significance level.

The MAE (Mean Absolute Error) is the average absolute difference between Interpolated data and UFV WO, furthermore, it provides the mean of the absolute estimation error. The interpolated data is close to the weather stations but each difference between the UFV WO weights the result.

The MBE (Mean Bias Error) gives information about the bias in estimation error and be negative values show how the Interpolated date is underestimated for UFV WO. The ideal value is tending to zero.

The RMSE (root mean square error) related the value to the standard deviation of the errors. RMSE closer to zero shows a better quality for the values. But for estimation purposes, the values are good.

R^2 shows the relation between actual and estimated value. The determination coefficient R^2=1 means a perfect estimation, so the results are good. The Table 1 shows the results about this comparison study for these different parameters.

Tab. 1: Analyze the interpolation data and the UFV WO data for different ways

Parameter	Value	Variables
KSI Test	$p = 1.0500x10^{-21}$ and h=1	UFV WO
KSI Test	$p = 6.6189x10^{-24}$ and h= 1	Interpolated data
MAE	116.9753 [W/m²]	Interpolated data and UFV WO
MBE	-1.65723[W/m²]	Interpolated data and UFV WO
RMSE	166.8271 [W/m²]	Interpolated data and UFV WO
R^2	0.7193	Interpolated data and UFV WO

For reference, the statistical error metrics for day-ahead forecast in hourly intervals realized by (Amanpreet Kaur, 2016) shows the method North American Model (NAM) as MAE=109.86, MBE=-69.65, RMSE=166.94 and R^2=0.72. The performance of the NAM model is extensively evaluated.

7. Conclusions

This numerical interpolation used in this work is able to estimate the Global irradiance for locations inside an area among the weather stations. This is done using data from three weather stations, located at the corners of the area of interest (a triangle), which are then interpolated, using weights, to produce solar resource information for points of interest located inside the triangle. For validation purpose, the interpolated results were compared with the power output of a PV plant (in the same location, obviously), translated to Global irradiance.
It is important to notice that this method is prone to errors due to the characteristic of microclimates, which also pose difficulties to other estimation methods. Giving the quality of the results, that the proposed method is good enough to make a first analysis of Global irradiance on places without direct Global irradiance measurements.
The time period for this simulation was April, March and beginning of April. In Brazil, up until March 20th is summertime and after is autumn, so this work happen is the change of seasons.
The time period for this simulation can be extended for draw better conclusions about this method. It is need to understand how the others seasons behave for this study.

8. Acknowledgments

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