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Special Edition

Monitoring of photovoltaic systems using different solar radiation and temperature databases

Monitoramento de sistemas fotovoltaicos utilizando diferentes bases de dados de radiação solar e temperatura

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ABSTRACT

With the demand for electricity growing, the migration to renewable sources is a reality. In distributed generation, photovoltaic systems are a renewable and sustainable alternative to the main energy sources to generate electricity. Monitoring a photovoltaic system over its operating time guarantees its good performance. This requires solar radiation and temperature data measured at the installation site or the use of solarimetric stations databases. However, the differences between the results simulated with databases and with data measured at the installation site are not widely known, which would be the ideal case from a technical point of view. The aim of this study was to verify the feasibility of monitoring the performance of a 2.5 kWp photovoltaic system located in the city of Porto Alegre - Brazil using the System Advisor Model (SAM) modeling tool and a public database. Simulation results were compared using data provided by a station of the National Institute of Meteorology (INMET) with the results obtained with data measured at the site of the photovoltaic system. Differences were verified between the solar radiation measured on site and that of the INMET database, and the difference in accumulated radiation was 9.2% for the entire period analyzed. When comparing the measured and simulated alternating current energy using the radiation and temperature data measured on site for the non-shading time, it was found that the difference between the results was 0.5%. Using the INMET climate file, the monthly differences ranged from -6% to 14% and the difference in accumulated energy for the entire measurement period was 2.5%. The results showed that the use of a database measured by a public solarimetric station close to the site, in this case approximately 6 km away from the installation, is feasible for monitoring photovoltaic systems, since the differences found were not significant. This monitoring can identify system failures and performance loss over time.

Keywords: Photovoltaic; Monitoring; Data base

RESUMO

Com a demanda por energia elétrica crescendo, a migração para fontes renováveis é uma realidade. Na geração distribuída, os sistemas fotovoltaicos são uma alternativa renovável e sustentável às principais fontes de energia para gerar eletricidade. Monitorar um sistema fotovoltaico ao longo do tempo de operação garante o seu bom desempenho. Para isso, são necessários dados de radiação solar e temperatura medidos no local da instalação ou a utilização de bancos de dados de estações solarimétricas. Porém, ainda não são amplamente conhecidas as diferenças entre os resultados simulados com bancos de dados e com dados medidos no local da instalação, que seria o caso ideal sob o ponto de vista técnico. O objetivo deste estudo foi verificar a viabilidade do monitoramento de desempenho de um sistema fotovoltaico de 2,5 kWp localizado na cidade de Porto Alegre - Brasil fazendo uso da ferramenta de modelagem *System Advisor Model* (SAM) e um banco de dados público. Foram comparados os resultados de simulação utilizando dados fornecidos por uma estação do Instituto Nacional de Meteorologia (INMET) com os resultados obtidos com dados medidos no local do sistema fotovoltaico. Foram verificadas diferenças entre a radiação solar medida no local e a do banco de dados do INMET, sendo que a diferença na radiação acumulada foi de 9,2% para todo o período analisado. Ao comparar a energia em corrente alternada medida e a simulada utilizando os dados de radiação e temperatura medidos no local para o horário sem sombreamento, verificou-se que a diferença entre os resultados foi de 0,5%. Com o uso do arquivo climático do INMET, as diferenças mensais variaram em torno de -6% a 14% e a diferença em energia acumulada para todo o período de medição foi de 2,5%. Os resultados mostraram que o uso de uma base de dados medidos por uma estação solarimétrica pública próxima ao local, no caso distante aproximadamente 6 km da instalação, é viável para o monitoramento de sistemas fotovoltaicos, uma vez que as diferenças encontradas não foram significativas. Este monitoramento pode identificar falhas no sistema e perda de desempenho ao longo do tempo.

Palavras-chave: Fotovoltaico; Monitoramento; Base de dados

1 INTRODUCTION

Currently, the growing demand for electric energy and the seek to reduce the use of fossil fuels in its generation have been causing a great change in the global electric sector. The use of conventional sources for energy generation, such as oil, natural gas and mineral coal, which tend to be scarce, leads to the emission of polluting gases, aggravating the greenhouse effect. Therefore, the search for alternative and renewable energy sources such as solar photovoltaics is increasing and studies on these technologies are becoming increasingly important (EPE, 2018).

The energy generated by a photovoltaic system varies according to several parameters such as solar radiation (solar energy per unit area) and ambient temperature (CAMARGO FRANCISCO *et al*., 2019). Thus, the accurate measurement of this data close to the system's installation site is important to obtain a more assertive forecast of the performance of photovoltaic projects and guarantee the return on the initial investment (MURAT ATES; SINGH, 2021).

Solar radiation measurements are still very scarce depending on the location and time scale of measurement. Global solar radiation reaching the earth's surface is made up of two components: direct and diffuse. Direct radiation is the portion of solar radiation that arrives directly (without suffering deviation) from the solar disk on the surface of the ground, and diffuse radiation is the portion of solar radiation that has been scattered into the atmosphere. In order to more accurately assess the solar resource available on an inclined surface, such as a photovoltaic module, it is convenient to have measured data with good precision from these two components. This information can be measured using solarimetric stations with equipment such as the pyranometer and the pyreliometer. However, the high cost of installation and operational maintenance of this equipment for each individual distributed generation unit can make this process practically unfeasible economically (SCOLAR; MARTINS; ESCOBEDO, 2003). Most of the meteorological databases currently available do not present the measurements of these components, having only values of global solar radiation on the horizontal surface, which makes the study of seasonality unfeasible, and can generate uncertainties in the estimates of the incidence of solar radiation on a surface leaning (DE SOUZA *et al*., 2010).

Several empirical models were developed in order to decompose the global component of horizontal solar radiation and estimate the values of diffuse and direct radiation incident on a horizontal surface. Based on measurement data at different locations,Liu e Jordan (1960) showed relationships between the global and diffuse component of solar radiation on a daily scale for days with clear skies and for different degrees of cloudiness. Orgill e Hollands (1977) e; Erbs, Klein e Duffie (1982) presented the relationship between the hourly diffuse solar radiation fraction and the hourly brightness index (k_T). Reindl, Beckman e Duffie (1990) added to these studies the influence of variables such as solar elevation, ambient temperature and relative humidity in the determination of the hourly diffuse fraction and showed a significant reduction in errors associated with previous studies. Batlles *et al*. (2000) verified that for days with cloudy skies and higher solar elevation angles, it is possible to estimate direct radiation values with errors close to 14% in relation to the average of the measured values using empirical modelling. This information is useful for the simulation of the energy efficiency of photovoltaic systems, being a less costly alternative in relation to the data measured in loco. The number of installed photovoltaic systems has been increasing gradually and, as a consequence, the technical and economic feasibility studies for different types of systems have also increased. (HAFFAF *et al*., 2021). Kazem *et al*. (2014) studied for six months the technical and economic feasibility of a photovoltaic system installed in Oman, using an hourly basis of measured data on solar radiation and ambient temperature. Dimas, Gilan e Aris (2011) reported that results for predicting the performance of photovoltaic systems using hourly solar radiation data as a reference are more reliable than when using data on a daily or monthly scale.

Considering the importance of monitoring photovoltaic systems and the difficulty of measuring solar radiation and ambient temperature data at the installation site, measurement databases from solarimetric stations are an alternative that enables the performance analysis of these systems. Okello *et al*. (2015) found a difference of 3% in the performance results of a 3.2 kWp photovoltaic system with simulations performed in the PVSyst software, using data measured in South Africa and Meteonorm, a database developed by Meteotest and widely used as a reference in the photovoltaic solar industry. In Suriname, Raghoebarsing e Kalpoe (2017) monitored a 27 kWp grid-connected photovoltaic system. The results showed a difference of 6% between measured and simulated data.

In this context, the analysis of the results of the monitoring carried out using databases is essential. The objective of this work was to verify the feasibility of monitoring the performance of a photovoltaic system through an hourly database of horizontal global solar radiation measured by a solarimetric station with public data and in the same city as the photovoltaic system. For this, the power in alternating current (AC) at the output of an installed photovoltaic system was monitored. The system's AC power measurements were compared to simulation results performed by the System Advisor Model (SAM) software with two input databases: 1) using data on global horizontal radiation, horizontal diffuse radiation and ambient temperature measured at the site and 2) a database measured by a solarimetric station from the National Institute of Meteorology (INMET).

2 MATERIALS E METHODS

This section discusses the methodology used to carry out the study. In the first part, a brief description of the characteristics of the photovoltaic system in the laboratory used as the object of study is presented. In the second, measurement equipment and data acquisition at the installation site were described. Next, the use of publicly available INMET and NREL databases and the consequent treatment of these data was explained. Finally, the use of the SAM modeling tool to obtain the results of energy generated by the photovoltaic system through a simulation was addressed.

2.1 Photovoltaic System

The photovoltaic system used as the basis for the study is installed in Porto Alegre (30°S'51°W) on the roof of the Solar Energy Laboratory (LABSOL - UFRGS), located on the Campus do Vale of the Federal University of Rio Grande do Sul. To capture the incident solar radiation, the system has 10 photovoltaic modules of 60 polycrystalline silicon cells (Yingli YL245P-29b). The modules have 15.1% of nominal efficiency, 245 Wp of power and are connected in series, totaling a nominal power of 2.45 kWp. The modules are oriented to geographic north with an inclination of 50° to the horizontal, as shown in Figure 1.

Figure 1 – Photovoltaic system installed at the Solar Energy Laboratory in Porto Alegre (UFRGS)

Source: Authors, 2021

Due to the characteristics of the building, the inclination of the modules is not ideal for the greatest use of energy production in the geographic coordinate of the location, which would be 30°. Another aspect that can be seen in Figure 1 is the presence of shading, which must be avoided in photovoltaic systems. In the specific case, the system is for academic use and the shading is somewhat purposeful, allowing the analysis of the impacts of shading on system performance, a topic that will not be addressed in this work. During the monitoring and maintenance period, the modules were not cleaned.

A 2500W inverter (Sunny Boy SB2500) and 93% nominal efficiency was installed to carry out the conversion of direct current (DC) into alternating current (AC) and the connection to the distributor's electricity supply network. The technical specifications of the inverter and modules under standard test conditions (STC) are described in Tables 1 and 2, respectively.

Table 1 – Technical characteristics of the Yingli module (YL245P-29b)

Photovoltaic Module		
Output power (P_{MAX})	245	W
Tolerance (ΔP_{MAX})	0/+5	W
Module efficiency (η_M)	15,1	%
Voltage at Pmax (V_{MPP})	29,6	V
Current at Pmax (I_{MPP})	8,28	A
Open circuit voltage (V_{OC})	37,5	V
Short circuit current (I_{SC})	8,83	A

Source: Datasheet Yingli Solar

Table 2 – Technical characteristics of the Sunny Boy SB2500 frequency inverter

Frequency inverter		
Rated AC power (P_{CAnom})	2300	W
Voltage range of the maximum power point tracking (ΔV_{MPPT})	224 – 480	V
Maximum DC current (I_{CCmax})	12,5	A
Network frequency (f_{NOM})	50/60	Hz
Inverter efficiency (η_{INV})	93,2	%
Rated AC current (I_{NOM})	10	A

Source: Datasheet SMA Solar Technology AG

2.2 Data measured at the installation site

In this study, two pyranometers were used to measure solar radiation at the system location: one to measure the global horizontal solar irradiance, the other configured with a shading ring to measure the diffuse horizontal solar irradiance. The shading ring obstructs the direct component of solar irradiance throughout the day, allowing to measure only the value of the diffuse component, as shown in Figure 2.

Figure 2 – Pyranometer with attached shading ring to measure horizontal diffuse solar radiation

Source: Authors, 2021

The ring was periodically adjusted manually, and its measurement results were corrected through correction factor F_C, according to the table presented in the equipment manual (KIPP & ZONEN, 2004), in order to compensate for the diffuse portion of the sky blocked by the shading ring. A reference photovoltaic cell was used to measure the global solar irradiance in the module plane, and the ambient temperature measurement (T_{AMB}) occurred by Pt100 type sensors.

The wind speed values at the installation site were not measured during the evaluation period and therefore are not part of the surveyed data file. The readings of incident solar radiation, ambient temperature and power in instantaneous alternating current at the inverter output were taken. The averages were calculated at twenty-minute intervals and stored by the data acquisition system (SMA SBCOP02 Sunny Boy) from August 27, 2020 to December 31, 2020. These values were compiled and transformed into hourly averages using computational tools. Due to the fact that the SAM software requests weather files with an hourly database at least one year apart at the input, the on-site measurements file was supplemented with a TMY (Typical Meteorological Year) data. In this sense, the amount of data obtained was sufficient for the proposed analysis, despite being an interval of less than one year.

2.3 Data base INMET-NREL

Global solar radiation values in the horizontal plane (I) and ambient temperature (T_{AMB})in one-hour intervals were supplied by INMET's A-801 automatic station, located approximately 6 km away from the analyzed photovoltaic system. In addition, the SOLPOS-NREL model was used to obtain extraterrestrial horizontal global solar radiation I_O (no atmospheric influence) and zenith angle θ_z (angle between the sun rays and the vertical) also in hourly scale. The rare lack of data measurement, due to instrumental errors and inconsistent data, was manually corrected. Extraterrestrial radiation values and zenith angles in the middle of each hour of the day were used in the calculations (also provided by SOLPOS-NREL), characterizing the radiation at the center of the one-hour interval. With the values of I and I_O, it was possible to calculate the hourly brightness index (k_T) according to eq. (1):

$$k_T = \frac{I}{I_O} \tag{1}$$

This index is the ratio between the hourly horizontal global solar radiation component and extraterrestrial solar radiation, and describes the loss of solar energy in the atmosphere due to scattering and cloudiness in the sky. Through these results, the empirical modeling proposed by Erbs *et al*. (1982) to obtain the hourly fraction of horizontal diffuse solar radiation, according to eq. (2):

$$\frac{I_d}{I} = \begin{cases} 1 - 0.09k_T & k_T \leq 0.22 \\ 0.9511 - 0.1604k_T + 4.388k_T^2 - 16.638k_T^3 + 12.336k_T^4 & 0.22 < k_T \leq 0.8 \\ 0.177 & k_T > 0.8 \end{cases} \tag{2}$$

These empirical equations correlate the hourly fraction of horizontal diffuse solar radiation and the k_T for different intervals of the hourly brightness index. Using the horizontal global solar radiation and the I_d/I ratio, it was possible to obtain the horizontal diffuse solar radiation I_d at intervals of one hour.

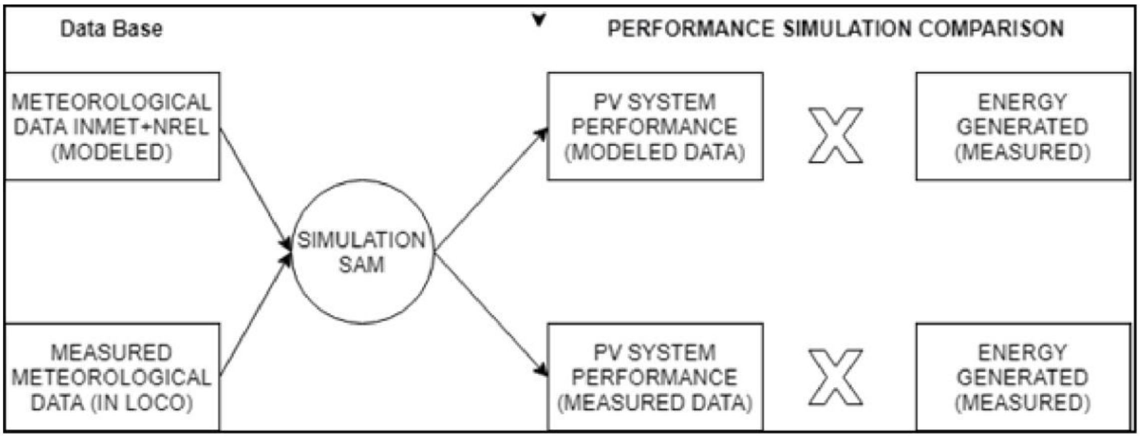
Knowing that the global horizontal solar radiation is the sum of the diffuse and direct components, to calculate the of direct solar radiation component normal to the horizontal plane ($I_{b,n}$),it was used eq. (3):

$$I_{b,n} = \frac{I - I_d}{cos\theta_z} \tag{3}$$

2.4 System Advisor Model – SAM

There are now several software on the market that help designers to make decisions regarding the technical and economic feasibility of using solar energy to produce electricity. The performance simulation of the photovoltaic system was performed using SAM (BLAIR *et al*., 2018). SAM is a computational modeling tool developed by the National Renewable Energy Laboratory (NREL) that allows you to perform energy and financial analysis of photovoltaic systems and various other renewable technologies. Two different simulations were carried out in order to analyze the difference between the results from measured data and those obtained from an INMET database. A detailed photovoltaic system model was used in this study, where parameters such as the module and inverter catalog data described in Tables 1 and 2, and the weather files with the hourly values of solar radiation were entered in the software interface global horizontal (I), horizontal diffuse solar radiation (I_d), normal direct solar radiation ($I_{b,n}$) and ambient temperature (T_{AMB}). Figure 3 outlines, through a flowchart, the simulations carried out and the process of comparing the results.

Figure 3 – Flowchart of simulations made in SAM for the photovoltaic system (SF)



Source: Authors, 2021

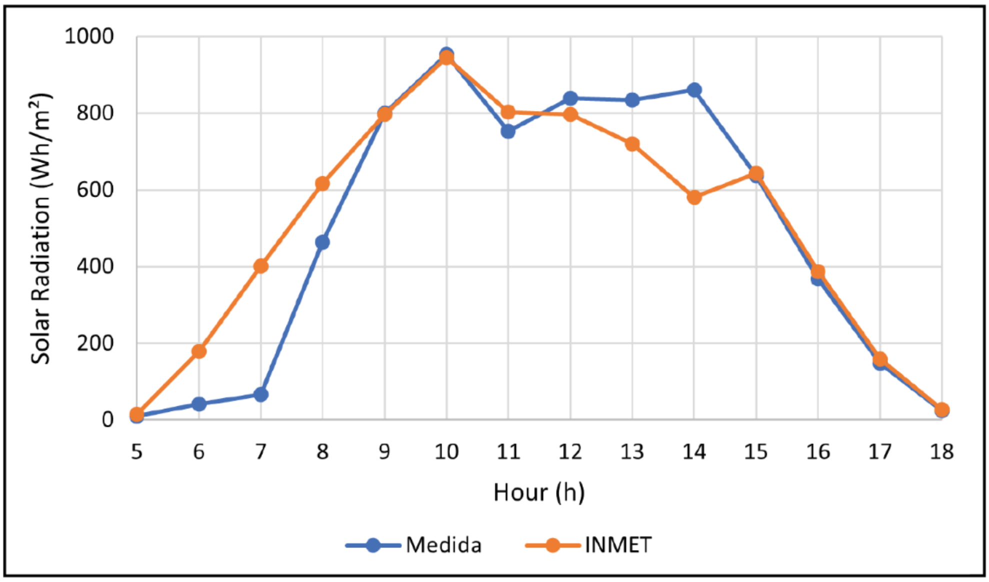
Through the use of variables I and Id, and the Perez diffuse sky model (PEREZ *et al*., 1987), it was possible to calculate the diffuse and direct solar radiation incident on the inclined plane of the modules, the component of radiation reflected in the ground and, consequently, the energy generated by the photovoltaic system in both cases. The first analysis was aimed at testing SAM as a monitoring tool when fed with hourly measured data. The SAM is normally used as a design and energy production estimation tool, and therefore, the differences in the results of generated energy over the four months when compared to the data stored in the datalogger were evaluated.

The photovoltaic system studied, as shown in Figure 1, is shaded in much of the morning and afternoon by surrounding elements. In order to remove interferences in the modeling, the period of the day without any shading at any time of the year (from 11 am to noon) was considered to compare the simulated AC power with the AC power measured by instrumentation. Two simulations were carried out with different climate files: one with data measured on site and the other with data from a solarimetric station. The simulations in the SAM did not consider the partial shading of the photovoltaic system, as the differences related to the shading model considered by the SAM would add up or would not make the differences caused by the database evident.

3 RESULTS E DISCUSSION

The solar radiation data from INMET's measurement and meteorological station, in addition to the results obtained in the SAM using the described methodology are analyzed in this section. The maximum measured value of horizontal global solar radiation, on December 22, 2020 at 12 o'clock, was 1204 Wh/m². In the INMET database, the maximum value found was 1094 Wh/m² on November 21, 2020. Figure 4 shows the hourly solar radiation measured on site and that obtained by INMET along December 2, 2020. At certain times in the morning, solar radiation measured on site is lower than that in the INMET database, while solar radiation measured on site is higher just after midday. However, the accumulated daily radiation measured by INMET is around 4% greater than that measured at the site on that day.

Figure 4 – Hourly radiation measured at the site of the photovoltaic system and by INMET on December 2, 2020

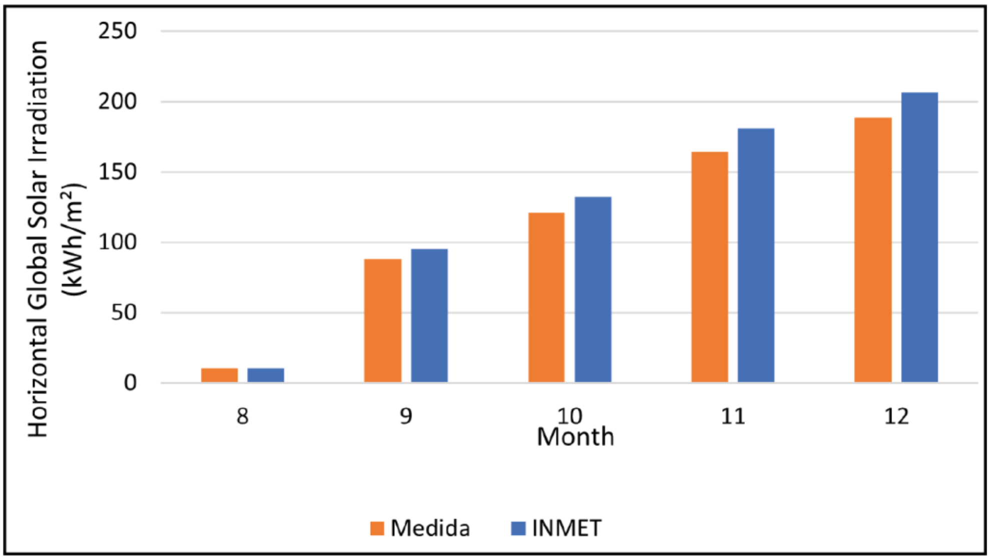


Source: Authors, 2021

Figure 5 shows the monthly horizontal global solar irradiation values (considering the measurement period) in kWh/m² for both data sources. As the month of August has few measurements performed, its values were considered for comparison purposes only. The values measured on site and obtained by INMET of total horizontal global solar radiation accumulated over the period in question are respectively 572 kWh/m² and 624 kWh/m². The difference between the total radiation obtained by the INMET data in relation to the measured data is 9.2% for the entire measurement period.

The differences between the solar radiation data measured on site and by INMET can be related to the measurement and calibration uncertainties of the equipment used at the site and at the INMET station, in addition to differences in local conditions. These local differences can occur due to the passage of clouds, which arrive at the PV installation and the solarimetric station at different times of the day. Therefore, the differences tend to reduce when comparing accumulated values of solar radiation, increasing the analyzed time interval. It is noteworthy that the values found are specific to the situation considered and that they depend on the installation location, the distance from the solarimetric station and the uncertainties of the equipment used.

Figure 5 – Measured monthly horizontal global solar irradiation and INMET values from August to December 2020

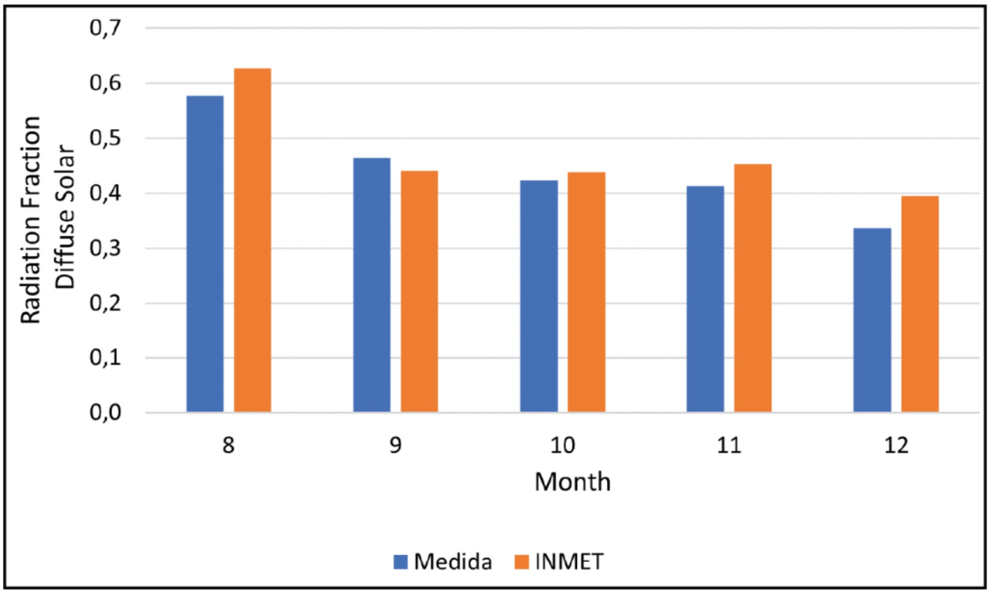


Source: Authors, 2021

The portion of the diffuse radiation in the horizontal global solar radiation is an important parameter to check the clarity of the sky. The greater the participation of diffuse radiation, the less clear the sky is. In Figure 6, the accumulated monthly values for both data sources are presented. The results obtained over the period in question by calculating with the measured data and with the INMET data are, respectively, 0.40 and 0.43.

Table 3 presents the values of energy generated by the photovoltaic system measured at the inverter output and simulated with both data sources considering only the unshaded time, from 11 am to noon. The differences in the simulated and measured monthly energy for the same time are shown in Table 4. The monthly differences ranged from -6.0% to 14.0% using the INMET database. When solar radiation data measured on site were used in the simulation, the differences in monthly energy were smaller, ranging from -3.4% and 3.8% as shown in Table 4.

Figure 6 – Diffuse solar radiation fraction measured and calculated with INMET data from August to December 2020



Source: Authors, 2021

Table 3 – Monthly energy in accumulated AC generated from 11 am to noon

Month	Measured Energy (kWh)	Simulated Energy SAM – INMET (kWh)	Simulated Energy SAM – Measured (kWh)
8	3,42	3,22	3,51
9	22,58	22,29	23,43
10	27,76	26,41	27,68
11	29,53	33,68	30,39
12	33,09	33,66	31,96
Total	116,38	119,26	116,97

Source: Authors, 2021

Table 4 – Difference in monthly energy in AC simulated and measured between 11 am and noon

Month	SAM – INMET	SAM – Measured
8	-6,0%	2,4%
9	-1,3%	3,8%
10	-4,9%	-0,3%
11	14,0%	2,9%
12	1,7%	-3,4%

Source: Authors, 2021

One of the most important steps in a simulation is the definition of input parameters, since not all variables are controlled. In the case of PV systems in urban areas, the systems have complex surrounding elements that make it difficult to estimate some of these parameters, such as the albedo, in addition to these elements causing shading. The complexity of estimating input parameters and modeling shaded systems were analyzed by Chepp, Gasparin e Krenzinger (2021).

According to Table 5, the difference between the measured accumulated energy and that simulated by the SAM using the radiation data measured on site over the entire measurement period is 0.5%. Therefore, the result obtained shows the accuracy of the results obtained by simulation using the SAM. The accumulated

AC energy obtained by the simulation carried out using the INMET database had a difference of 2.5% in relation to the measurement. The difference found is smaller than the values found in the literature for simulations carried out in other places (OKELLO; VAN DYK; VORSTER, 2015; RAGHOEBARSING; KALPOE, 2017).

Table 5 – Energy produced accumulated throughout the period from 11 am to noon

	Measured	SAM – INMET	SAM – Measured
Energy (kWh)	116,38	119,26	116,97
Variation	-	2,5%	0,5%

Source: Authors, 2021

Differences were verified in the solar radiation measured on site and in the INMET database over the course of a day, but the difference over the entire period is 9.2%. Although the simulated monthly electrical energy is around 14% greater than that measured in November when the INMET database is used, the difference accumulated over the entire measurement period is less than 3%. The larger the range of data analysis, the differences in solar radiation and simulated electrical energy tend to decrease. Therefore, the differences between the simulated and measured results were not significant, showing that the use of a database from public solarimetric stations is an option considered viable for monitoring photovoltaic systems in distributed generation, since the measurement on site it is usually unfeasible for monitoring small systems. This method of monitoring can, for example, indicate the need to clean the modules, that is, when there is a tendency to reduce the energy produced and the difference between simulated and produced energy starts to increase and reach values in which the performance of the system compared to what was expected in the simulation is outside certain established limits. Monitoring also allows you to track and verify any unexpected system failures and quickly intervene. Without efficient monitoring with reliable solar radiation data it is not possible to verify that the system is operating as expected.

4 CONCLUSIONS

This study aimed to analyze the feasibility of monitoring photovoltaic systems using a database measured by a public solarimetric station, which is not in the same location as the photovoltaic installation. In this case, the station is in the same city, approximately 6 km away from the analyzed system. Solar radiation data measured at the photovoltaic installation site were compared with data obtained from an INMET station in a nearby region. In addition, the energy generated throughout the entire measurement period was read and compared with the energy simulated by the SAM tool, using as input a climate file with on-site measurement data and another with INMET data.

Comparisons of daily and monthly solar radiation data showed that there are differences between the values measured on site and by INMET, and throughout the entire measurement period the difference in accumulated radiation was 9.2%. When comparing the accumulated electricity generated from 11 am to noon (time without shade) throughout the measurement period, the result of the simulation performed with the measured climate file showed a 0.5% difference in relation to the energy value measured, confirming the accuracy of the results simulated by the SAM. The electrical energy estimated by simulations carried out with the INMET database showed an average difference of 2.5% in relation to the measured energy.

Therefore, the use of data from a solarimetric station close to the installation site is useful and viable for monitoring photovoltaic systems. Future studies, with the aim of automating the acquisition of data from stations and using this comparison methodology, can be carried out in order to obtain a market product in the area of monitoring and maintenance of photovoltaic systems, in which sharp deviations from the expected energy outside the accuracy limits of the methodology indicate some need for intervention in the system, either for cleaning or checking for some hidden defect.

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