Software Tool for Calculating Energy Weighted Coefficients in PV Inverter Efficiency Evaluation

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Abstract

The calculation of weighted coefficients is essential for accurately estimating the efficiency of photovoltaic (PV) inverters under real operating conditions. It enables fair comparisons between devices and better adaptation to the climatic characteristics of each region, contributing to the optimized selection of inverters and improved performance of PV systems. To enable the calculation of the weighted efficiency for different geographic locations, a dedicated algorithm was developed. This algorithm automates the generation of the weighted coefficients and was fully implemented as a software tool. The application is capable of processing large volumes of irradiance data, extracting the necessary information, and producing the weighted coefficients in a structured format. This work presents the design and implementation of an algorithm for calculating weighted coefficients, automated through a dedicated software tool.

Keywords: weighted coefficients, weighted efficiency, software tool, photovoltaic inverter

1. Introduction

The growing photovoltaic (PV) solar market has led to a greater variety of inverters and related products, creating the need for reliable methods to compare and select equipment. To choose the most appropriate inverter and accurately estimate system performance, standardized test procedures and efficiency measurements are essential. These follow both normative and commercial standards, ensuring reliable performance evaluations and helping consumers select the most suitable devices for their specific needs s (Bletterie et al., 2011).

As the variety of inverters increases, selecting the most appropriate technology becomes more complex. Factors such as conversion efficiency, response under partial shading, thermal performance, and long-term reliability must be considered. Accurate efficiency measurements are particularly critical, as they directly impact the expected energy yield of a system and influence economic viability. By adhering to standardized testing protocols, manufacturers and researchers ensure that performance comparisons are consistent and transparent, facilitating informed decision-making for both designers and end-users.

EURO (Hotopp, 1990) and CEC (Bower et al., 2004) efficiencies are widely recognized and used worldwide, often referred as weighted efficiencies, taking into account the local irradiance level and different input voltage profiles. Although the IEC 61683:1999 standard (Photovoltaic systems - Power conditioners - Procedure for measuring efficiency, 1999) addresses the concept and methodology of weighted efficiency, it does not specify the calculation procedure. On the other hand, the EN 50530:2011 standard (for Standardization, 2011) details the equations mentioned by the CEC and establishes requirements for standardizing the preparation of other weighted efficiencies.

It is important to note that despite the widespread use of EURO and CEC efficiencies, several academically developed weighted efficiencies exist worldwide, all with the aim of better representing the region in which they are applied. Table 1 presents the nineteen weighted efficiencies reported in the literature. It lists the name of each efficiency, its geographical location, whether irradiance on a fixed inclined plane was considered, if the data collection covered an entire year, and whether the temporal granularity of the data is within 15 minutes.

Although EURO and CEC efficiencies are widely used, numerous region-specific weighted efficiency metrics

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have been developed to better represent local conditions, detailing their origin, use of global tilted irradiance (GTI) data, year-round data collection, and data granularity (Bower et al., 2004; Hotopp, 1990).

Table 1: Review of existing weighted efficiencies.

Item	Efficiency	Location	GTI (W/m²)	1 year data	Granularity (15 minutes)
1	η_{EURO}	Trier, Germany (Hotopp, 1990)	✓	✓	x
2	η_{CEC}	Sacramento and California, USA (Bower et al., 2004)	✓	✓	✓
3	$\eta_{Chennai}$	Chennai, India (Kalathil and Krishnamurthy, 2014	x	✓	N.I.
4	η_{PHS}	Phitsanulok, Thailand (Ketjoy et al., 2021)	✓	✓	✓
5	η_{Bap}	Bap, India (Panwar et al., 2017)	N.I.	✓	N.I.
6	η_{Hainan}	Hainan, China (Panwar et al., 2017)	N.I.	✓	N.I.
7	η_{izm}	Izmir, Turkey (Ongun, Ozdemir, et al., 2013)	N.I.	✓	N.I.
8	η_{Kanpur}	Kanpur, India (Pillai et al., 2014)	N.I.	x	✓
9	$\eta_{Equatorial}$	Equatorial, Region Ab. (Ab. Rahman et al., 2020)	✓	✓	✓
10	η_{WCT}	Cape Town, South Africa (Byamungu, 2018)	✓	✓	x
11	η_{IDL}	Inidial, Brazil (Peres et al., 2017)	N.I.	✓	✓
12	η_{FNS}	Florianópolis (SC), Brazil (Péres et al., 2017)	N.I.	✓	✓
13	η_{IAI}	Itajai, Brazil (Péres et al., 2017)	N.I.	✓	✓
14	η_{SMS}	São Martinho (RS), Brazil (Dupont et al., 2014)	x	✓	✓
15	η_{ORN}	Ourinhos (SP), Brazil (Dupont et al., 2014)	x	✓	✓
16	η_{BRB}	Brasília (DF), Brazil (Dupont et al., 2014)	x	✓	✓
17	η_{PTR}	Petrolina (PE), Brazil (Dupont et al., 2014)	x	✓	✓
18	η_{PARANA}	Paraná, Brazil (Meneghette dos Santos, 2021)	✓	✓	x
19	$\eta_{BR,USP}$	Brazilian Efficiency, USP (Incropera et al., 2014 and Pinto et al., 2011)	✓	✓	✓

N.I. -- no information

According to international standards, the weighted efficiency of photovoltaic inverters is measured in a controlled environment using a simulator that replicates real conditions (Ab. Rahman et al., 2020). This paper presents the development of a software tool designed to process large volumes of irradiance data, perform data cleaning, and generate weighted coefficients in a structured format. The focus is placed on the design and functionality of the algorithm, as well as its implementation within the software environment.

2. Development of weighted coefficients by software tool

Following IEC 61683, CEC, and EN 50530:2011, the weighted efficiency of a PV inverter is determined in a controlled laboratory environment using a PV array simulator. This simulator replicates the operating conditions of a real PV module when connected to the inverter under test (Ab. Rahman et al., 2020). The inverter's input and output power data are recorded to calculate the efficiency. It is worth noting that the weighted efficiency is calculated by maintaining the temperature of the PV module constant at 25°C while only adjusting the solar irradiance to simulate different climatic conditions (Ab. Rahman et al., 2020).

When formulating the efficiency equation, the weighting coefficients indicate the proportion of time the inverter operates at different input power levels. To derive these coefficients for a given DC input power level of the inverter, data from the irradiance profile on the inclined plane must be used. This analysis assumes that the instantaneous irradiance corresponds to the instantaneous power of the PV modules, as defined in EN 50530.

Thus, the methodology for developing the weighted efficiency of a PV inverter in a specific location follows these four steps:

1. Use a Global Tilted Irradiance (GTI) database with at least one year's data. The standards CEC (Bower et al., 2004) and EN 50530:2011 (for Standardization, 2011) only mention the need to collect irradiance data on a fixed tilted plane. However, "IEC 61724: 2021 - Photovoltaic System Performance - Part 1: Monitoring", n.d. and "ISO 9060:2018 - Solar energy — Specification and classification of instruments for measuring hemispherical solar and direct solar radiation", n.d. require data to be collected at a maximum sampling rate of 15 minutes.
2. Distribute the irradiance ranges according to the selected loading, as specified in EN 50530:2011 (for Standardization, 2011).
3. Determine the weighting coefficients, for which it is necessary to calculate the integral of the irradiance area on the fixed tilted plane, for each irradiance range, in order to obtain the corresponding energy. These values are used to define the weighting coefficients, as shown in Table 2.
4. Draw up the weighted efficiency equation and calculate this efficiency using the weighting coefficients obtained previously. After following steps 1 to 3, it is possible to apply (eq. 1), as specified in standard EN 50530:2011 (for Standardization, 2011):

$$\eta_{location} = WC \cdot \eta_{10\%} + WC \cdot \eta_{20\%} + WC \cdot \eta_{30\%} + WC \cdot \eta_{50\%} + WC \cdot \eta_{75\%} + WC \cdot \eta_{100\%} \qquad \text{(eq. 1)}$$

where: $\eta_{location}$ is the efficiency of the chosen locality; WC is the weighting coefficient; $\eta_{X\%}$ represents the efficiency at $X\%$ of the load/power of the equipment under test.

Table 2: Weighted efficiency parameters for a given location.

Irradiance ranges (W/m²)	Loading (%)	Weighting coefficient
0 - 100	10	Irradiance Range Energy
101 - 200	20	Irradiance Range Energy
201 - 300	30	Irradiance Range Energy
301 - 500	50	Irradiance Range Energy
501 - 750	75	Irradiance Range Energy
>750	100	Irradiance Range Energy

The methodology used to calculate these coefficients, along with the specific procedures for determining efficiency at each level. To automatize the process, an algorithm was developed, which ended up as a software tool, as explained in the following.

2.1. Software development

For the programming and development of the software, historical irradiation data were required; in this example, information from the cities of São Paulo and Teresina was used. The software imports CSV files containing data from multiple locations and calculates the weighted coefficients for each city or state. The algorithm then aggregates the results by region, ultimately providing a representation of the overall efficiency across Brazil.

For that, a collection of GTI data (W/m^2) was obtained from the SolCast database with 5-minute intervals, as provided in CSV files. The data mining and formatting treatments were carried out using AppDesigner from Matlab software, as illustrated in Figure 1. For the software development tests, historical irradiance data from the cities of São Paulo and Teresina were used. The software is designed to load CSV files containing irradiance data from multiple cities and calculate the corresponding weighted coefficients for each location. Subsequently, the algorithm aggregates this information by region to provide a broader representation of inverter efficiency across Brazil.

To achieve this, GTI data (W/m^2) at 5-minute intervals were obtained from the SolCast database in CSV format. A dedicated database was then implemented within the software to store, manage, and process the data through a user interface, as illustrated in Figure 1.

Figure 1: Data flow for final processing.

The main objective of the software tool is to provide a structured framework for the treatment and analysis of irradiation data. This is achieved through a well-defined workflow that ensures data reliability, enhances interpretability, and supports decision-making. The procedure adopted in the software consists of the following steps:

- **Data import.** The first step consists of loading the data into the software tool environment. In this implementation, the tool supports input in ".csv"" format, which enables compatibility with common databases such as SolCast and other measurement systems. The import module was designed to handle large datasets efficiently, preserving time resolution and metadata for subsequent processing.
- **Data cleaning.** Once imported, the dataset undergoes a pre-processing stage to ensure consistency and reliability. This stage includes the detection and removal of duplicated records, correction of missing values through interpolation or statistical replacement methods, and elimination of outliers that may distort the results. By standardizing the dataset, this step guarantees that subsequent analyses are based on accurate and representative information.
- **Exploratory analysis.** After cleaning, the data are subjected to exploratory analysis to reveal underlying structures, patterns, and temporal variations. This step allows for a comprehensive understanding of the behavior of irradiation across different periods and regions, serving as a foundation for deeper analysis.
- **Data analytics.** In the final step, efficiency metrics are applied to assess how irradiation data contribute to national energy evaluations. In the Brazilian context, the software processes the dataset to estimate local or regional data and provide a weighted evaluation of overall efficiency at the national scale. The results from this stage can support planning strategies, and performance benchmarking of renewable energy systems.

2.2. Calculating the weighted coefficients

The procedure for calculating coefficients at different location levels follows the same methodology. To determine the overall Brazilian efficiency, the entire database is aggregated, treating multiple entries from the same location as distinct data points. The workflow can be described as follows:

i. Acquire irradiance data for a selected location (city, state, region, or country).

ii. Define the data granularity, which in this case corresponds to 5-minute intervals provided by the database.

iii. For each CSV file, extract the GTI irradiance values (G), discard zero entries, and generate a vector for each dataset. From the irradiance values, compute the corresponding energy (E).

iv. Construct a database containing the following fields: Location, Irradiance, and Energy. Identify unique entries in the *Location* column and determine the start and end indices for processing the data of each location.

v. Apply the same procedure to all CSV files, with each file representing a different location.

vi. Classify the irradiance and energy values according to the predefined ranges stored in vector *R*.

vii. For each range, compute: (a) the frequency of occurrence (number of repetitions), (b) the total accumulated energy.

viii. Finally, apply the weighted efficiency equation, incorporating energy weighting coefficients as defined in standard EN 50530:2011 (for Standardization, 2011), and expressed in (eq. 1).

In addition to the weighting factors, the corresponding load levels (uniform across all ranges) are also defined. In this work, the following classification vector is adopted: $R = [0, 100, 200, 300, 500, 750]$

Figure 2 shows the flowchart of the weighted coefficient generation process. The following steps are:

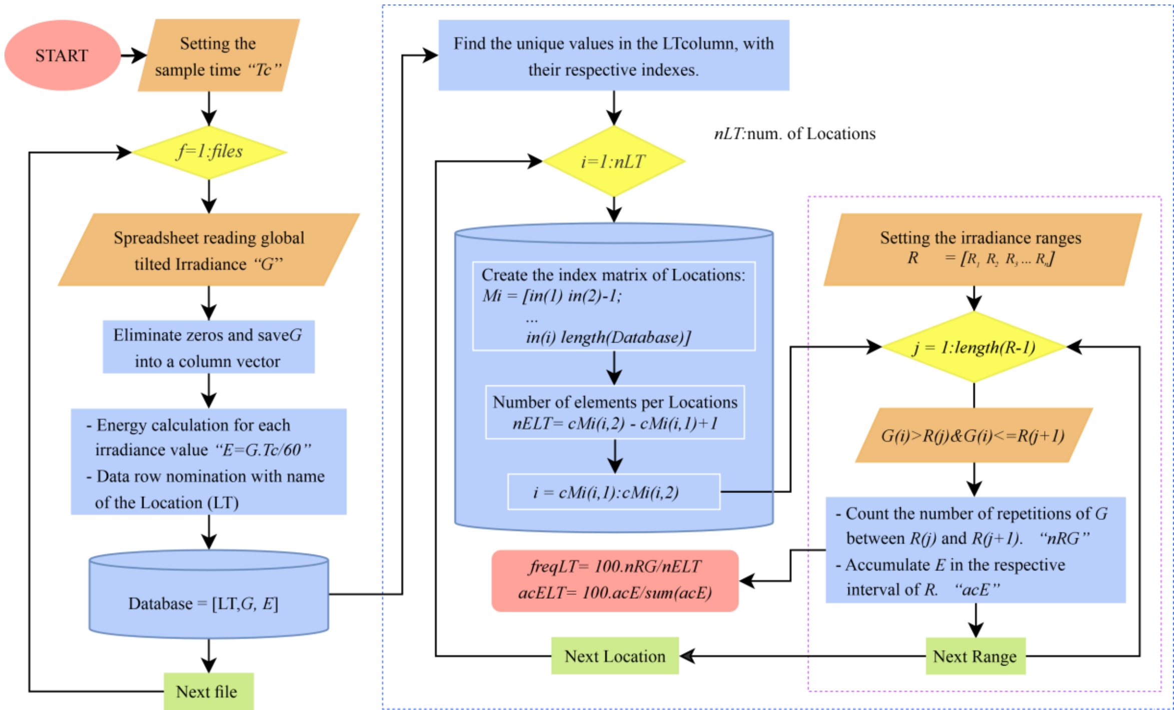


Figure 2: Flowchart of the weighted coefficients generation process.

2.3. Procedure for using the software tool

This app was developed to simplify installation and access. The installer file is only 12 MB, and users do not need a MATLAB license to run the application. When executing the installer, a series of setup screens will appear as shown below. Simply click NEXT until the installation is complete.

The following steps must be completed to ensure the proper calculation of the efficiency coefficients:

step 1: Click on the UPLOAD button. After this action, a window will open allowing the user to select the FILE (.xlsx) stored on their computer. This file is used as the data reference for the data mining stage that will begin when step 4 is started. As shown in Figure 3, the circular indicator will change to a green light, and the rectangle will show the data.

step 2: To select the period to be analyzed (in this example, between January 2014 and December 2023). To choose a time interval greater than or equal to five minutes. To proceed to Step 3 and select one of the available options: (Brazilian) Cities, States, or Regions.

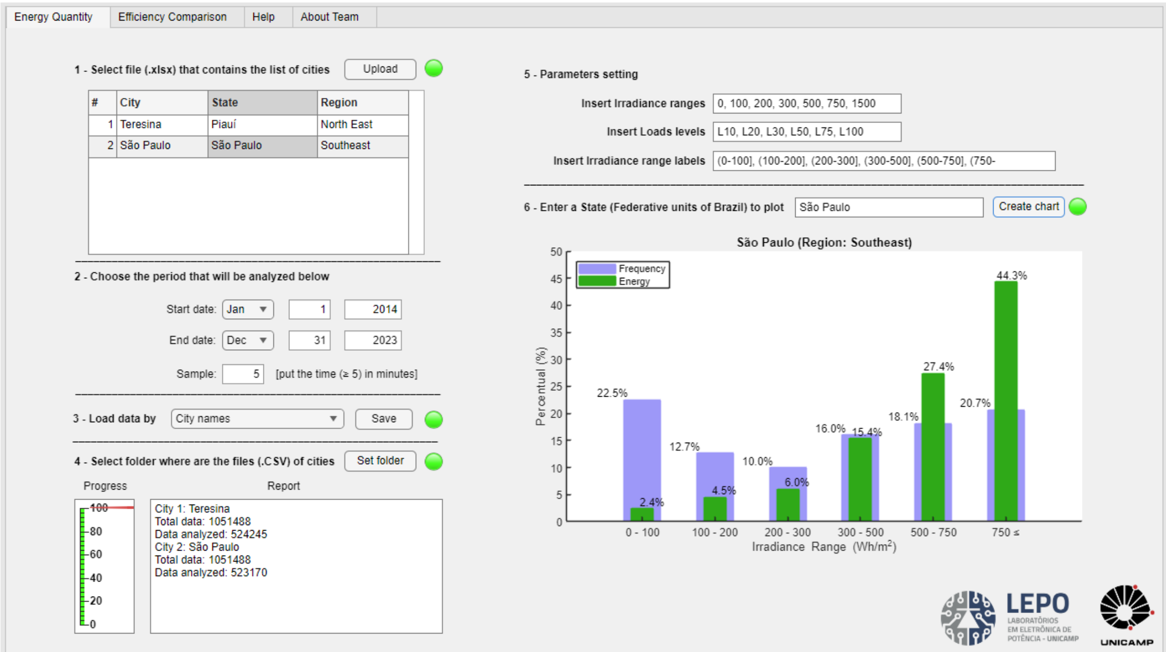
step 3: This variable must contain the names of the collected files, in this example, to select "Cities", and to click the SAVE button. After this action, to observe that the circular indicator turns yellow, changing color again after completing Step 4.

step 4: In this context, city names will be used as variables to load the files, which will be renamed according to the corresponding city. Before loading the city files, it is necessary to correctly follow step 2 to obtain the desired period's irradiance and photovoltaic energy forecast. Upon starting the process, the circle of item 3 turns green and item 4 turns yellow. The loading progress can be monitored on the progress bar. When it reaches 100% and the circle of item 4 changes to green, as shown in Figure 3, the user can perform the actions of step 5.

step 5: After concluding step 4. The irradiance interval, load level, and range of irradiance are required to be set on item 5. The app automatically shows the default settings.

step 6: At item 6, there is a space to write the Brazilian State name that the user wants to see data on the graphic, as depicted in Figure 3. The list with the states is shown in item 1 of this window. After concluding, press the button to see the chart.

In this example, presented in Figure 3, São Paulo state was chosen to display the data chart. for other states, repeat step 4 as many times as necessary.



#	City	State	Region
1	Teresina	Piauí	North East
2	São Paulo	São Paulo	Southeast

Figure 3: Screenshot of the developed software tool.

The software is designed to load CSV files containing irradiance data from multiple cities and calculate the corresponding weighted coefficients for each location. Subsequently, the algorithm aggregates this information by region to provide a broader representation of inverter efficiency across Brazil.

3. Results

In this section, the step-by-step procedure of the implemented algorithm within the software is presented. The process begins with the acquisition and organization of irradiance data, followed by the computation of the corresponding energy and the application of the weighting efficiency methodology. The detailed sequence is described as follows:

i. Data acquisition.

Collect irradiance data corresponding to selected geographical locations, specifically the states of Piauí and São Paulo. The data are imported from CSV files containing ten years of historical Global Tilted Irradiance

(GTI) records.

ii. Time granularity specification.

Define the temporal resolution of the dataset, denoted as the time granularity (*TG*), which in this study is set to 5-minute intervals, as provided by the SolCast database. This resolution ensures adequate temporal detail for analyzing the irradiance and energy profiles.

iii. Data processing and energy calculation.

For each CSV file, extract the GTI values. First, all zero or invalid entries are discarded to prevent distortions in subsequent analyses. Then, from the valid irradiance data G, compute the corresponding energy values E over each time interval, thereby generating a representative energy vector for the dataset. This energy calculation is expressed by:

$$E(n) = GTI(n) \times \frac{TG}{60} \quad \text{(eq. 2)}$$

Where *n* represents the sample corresponding to the selected time granularity, and *GTI(n)* has no zero values.

Figures 4 and 5 illustrate the mission profiles generated from ten years of GTI data for the states of Piauí and São Paulo, respectively. In these figures, the gray curve represents the raw irradiance data measured over the full observation period, while the blue curve corresponds to the accumulated energy computed from those irradiance values.

Additionally, both figures include a zoomed-in view of a representative segment of the dataset, specifically, samples 4900 to 5200, to highlight the temporal variability of solar irradiance within shorter time frames. This detailed visualization provides insight into the fluctuations and intermittency of solar energy availability, which directly influence the dynamic response and efficiency of PV inverters operating under real-world conditions.

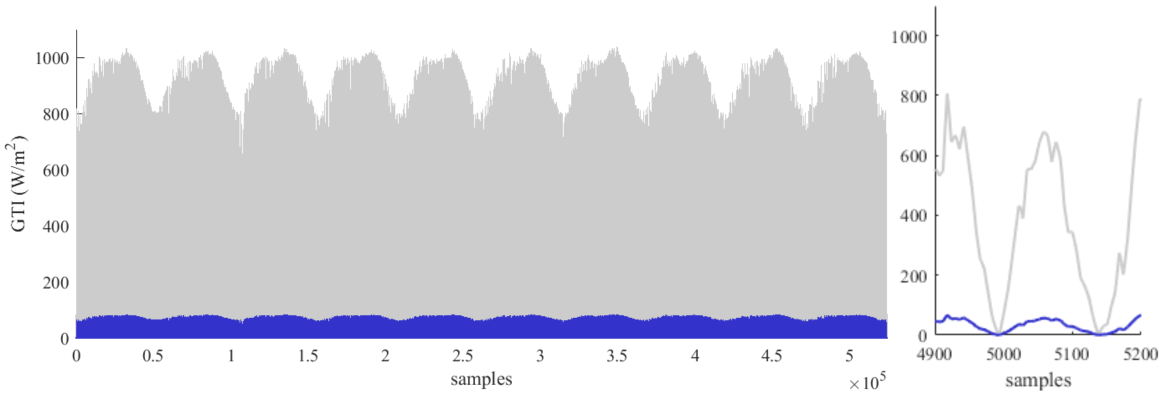


Figure 4: Mission profile of ten years of GTI data (gray) and Energy (blue) in the state of Piauí and details.

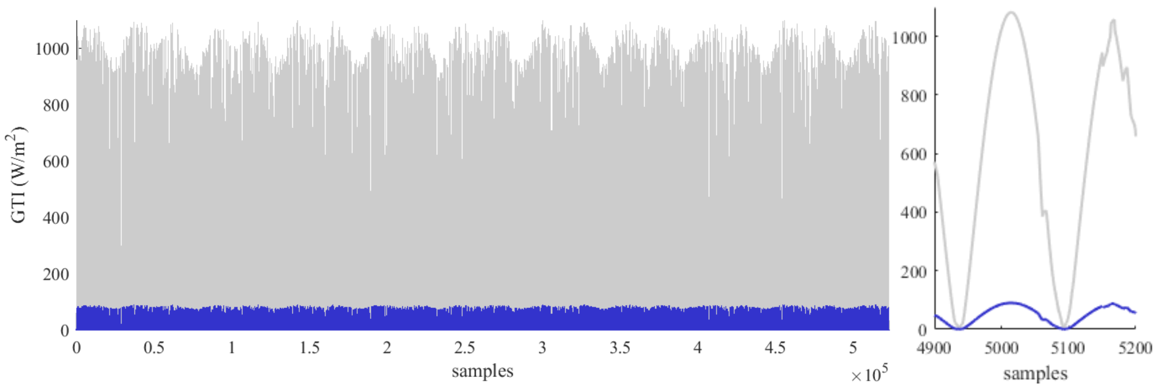


Figure 5: Mission profile of ten years of GTI data (gray) and Energy (blue) in the state of São Paulo and details.

iv. Database construction:

Construct a comprehensive database that includes the fields Location, Irradiance, and Energy. Identify the unique entries in the Location column and determine their respective start and end indices. These indices are used to segment and process the data corresponding to each specific location independently.

To achieve this, the first step is to calculate the index range matrix, defined as:

$$Mi = \begin{bmatrix} in(1) & in(2)-1 \\ \vdots & \vdots \\ in(i) & length(Database) \end{bmatrix} \quad \text{(eq. 3)}$$

where *i* represents the *i*-th city being processed, and *in* denotes the input data corresponding to a specific locality. In this way, the number of elements for each location (*nELT*) is obtained as:

$$nELT = cMi(i,2) - cMi(i,1) + 1 \quad \text{(eq. 4)}$$

where *cMi* represents the index vector of a specific city.

Therefore, the vector containing the indices for each location is given by:

$$i = cMi(i,1){:}\, cMi(i,2) \quad \text{(eq. 5)}$$

v. Multi-file integration:

Apply the same data extraction and processing procedure to all CSV files in the dataset, with each file corresponding to a distinct geographical location. The resulting processed data are then aggregated into a unified database for further analysis.

vi. Classification by Irradiance Ranges:

Classify the irradiance and energy values according to predefined irradiance ranges stored in vector *R*, which establishes the boundaries for the different operating intervals used in the analysis.

$$R = [0\ 100\ 200\ 300\ 500\ 750\ 1500] \quad \text{(eq. 6)}$$

vii. Statistical computation:

For each irradiance range, compute the following metrics:

(a) the frequency of occurrence, representing the number of samples falling within each interval, given by:

$$R(j) < GTI(i) \leq R(j) \quad \text{(eq. 7)}$$

(b) the total accumulated energy, obtained by summing the corresponding energy values within that range, with all elements being counted in the process.

$$\begin{cases} acE(j) = acE(j) + E(i) \\ countEL(j) = countEL(j) + 1 \end{cases} \quad \text{(eq. 8)}$$

viii. Weighted efficiency evaluation:

Finally, apply the weighted efficiency equation, which integrates the previously calculated energy weighting coefficients. This computation follows the methodology defined in the EN 50530:2011, and is mathematically expressed in (eq. 1). The resulting weighted efficiency provides a realistic estimation of the photovoltaic system's performance under dynamic irradiance conditions representative of real-world operation.

For each interval, the same process is performed to obtain the corresponding weighted coefficients, as defined by:

$$\begin{cases} energy = \dfrac{acE(j)}{\sum(Database.Energy)} \times 100 \\ frequency = \dfrac{countEL(j)}{heigth(Database)} \times 100 \end{cases} \quad \text{(eq. 9)}$$

where: *acE(j)* is the accumulated energy associated with the *j*-th interval; *Database.Energy* represents the total energy values in the dataset energy raw; *countEL(j)* corresponds to the number of elements within the *j*-th irradiance interval; and *height(Database)* denotes the total number of samples in the database.

These coefficients quantify the relative contribution of each interval in terms of both energy and occurrence frequency, serving as weighting factors in the overall efficiency evaluation.

- Once the weighted coefficients have been computed for a specific location, the inverter efficiency can be determined by applying the corresponding loading values associated with each defined load level, as summarized in Table 3. These load levels represent the normalized operating points defined in the EN 50530:2011 standard, which associates each irradiance interval with a characteristic DC input power level. By combining the weighted coefficients with the respective inverter efficiencies at these load levels, a comprehensive assessment of the inverter's dynamic performance can be achieved.
- Figures 6 and 7 present the distributions of frequency and energy for the cities of São Paulo and Teresina, respectively. These graphs illustrate the differences in irradiance profiles between both locations, highlighting the distinct patterns of solar resource availability and the resulting influence on the inverter's performance evaluation.

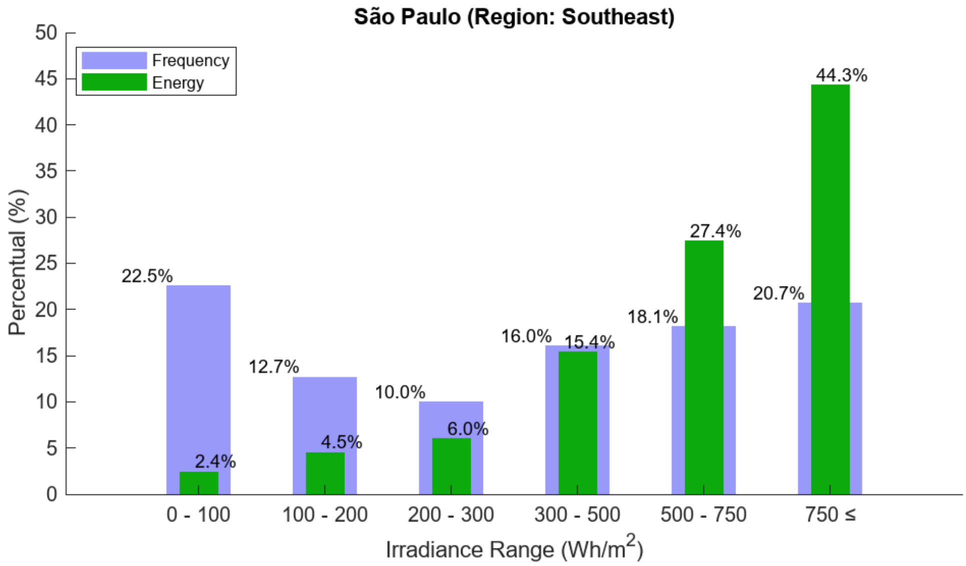


Figure 6: Mission profile of ten years of GTI

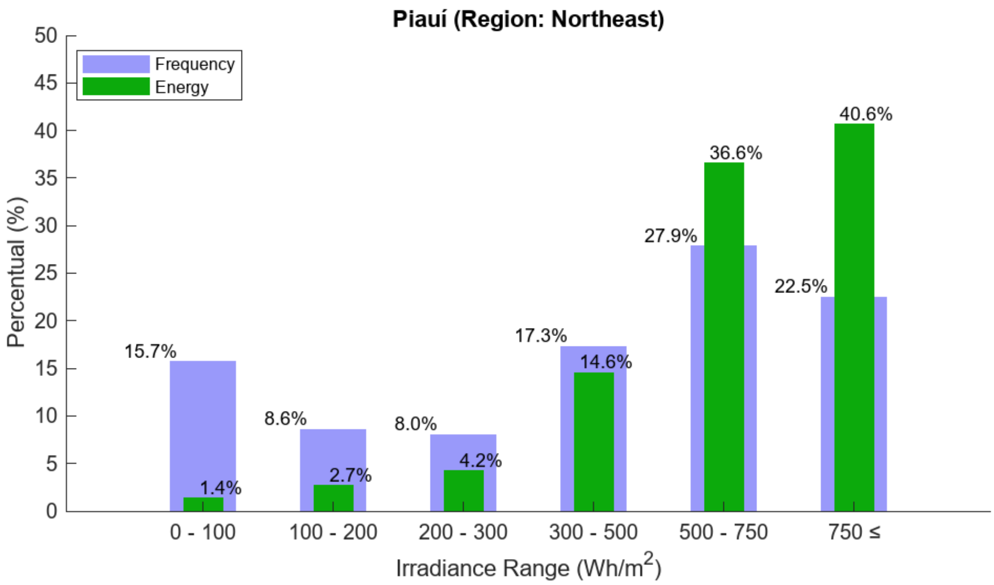


Figure 7: Mission profile of ten years of GTI

Table 3: Comparison of EURO, CEC and weighted coefficients of 2 Brazilian cities.

Efficiency	Loading (%)						
	5	10	20	30	50	75	100
EURO	3	6	13	10	48	--	20
CEC	--	4	5	12	21	53	5
Brazilian cities (%)							
Teresina	--	1.35	2.67	4.20	14.56	36.58	40.62
São Paulo	--	2.39	4.52	6.00	15.36	27.40	44.30

4. Conclusions

The developed software provides a comprehensive and automated framework for processing extensive solar irradiance datasets, such as ten years of data sampled at 5-minute intervals, to compute the weighted efficiency coefficients of PV inverters in accordance with the EN 50530:2011 standard.

By leveraging historical irradiance data from representative Brazilian cities, such as São Paulo and Teresina, the tool is capable of performing detailed energy-weighted and frequency-weighted analyses that accurately reflect local climatic and solar resource conditions. This enables the estimation of location-specific inverter efficiencies, allowing for a more realistic assessment of system performance under dynamic irradiance profiles. Furthermore, the methodology implemented in the software bridges the gap between laboratory-based static efficiency measurements and the variable operating conditions observed in real PV installations. As a result, the proposed approach enhances the precision of inverter characterization and contributes to regionally optimized equipment selection, ensuring that performance metrics are tailored to the actual solar potential of each site.

This procedure enables the evaluation of inverter efficiency under varying irradiance conditions representative of real-world operation. The weighted approach guarantees that intervals with higher energy contribution or occurrence frequency exert a proportional influence on the overall efficiency outcome.

In addition, the flexibility of the algorithm allows it to be easily extended to include other locations, datasets, or inverter technologies, thereby serving as a valuable decision-support tool for both research and practical applications in photovoltaic system design, performance benchmarking, and policy planning.

5. Acknowledgments

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