Brazilian Photovoltaic Potential

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Abstract

The expansion of the Brazilian energy matrix foresees the sharing of renewable sources with 48% of the internal energy supply in the next 10 years, in accordance with the Brazilian commitments to the United Nations Paris agreement on climate change (NDC). Among the various alternatives for renewable sources stands out the solar, which experienced a national growth at more than 250% in the last two years. In order to support this robust growth and to provide a reliable source of solar data, the mapping of the Brazilian solar potential was carried out using a radiative transfer model adjusted for the tropical climate in Brazil and employing 17 years of satellite data.

Keywords: Solar Energy, Photovoltaic Energy, Renewable Energy, Brazil,

1. Introduction

The Brazilian electrical system is primarily hydrothermal with a strong predominance of hydropower plants. The total capacity of power generation in Brazil reached the approximate mark of 624 TWh with the hydropower generation contributing with 65% (EPE/BEN, 2018). The Brazilian electrical system is all connected through the National Interconnected System (SIN) presenting size and characteristics considered unique worldwide. Isolated systems, located mainly in the Amazon region, serve only 1.7% of the total electricity demand in Brazil.

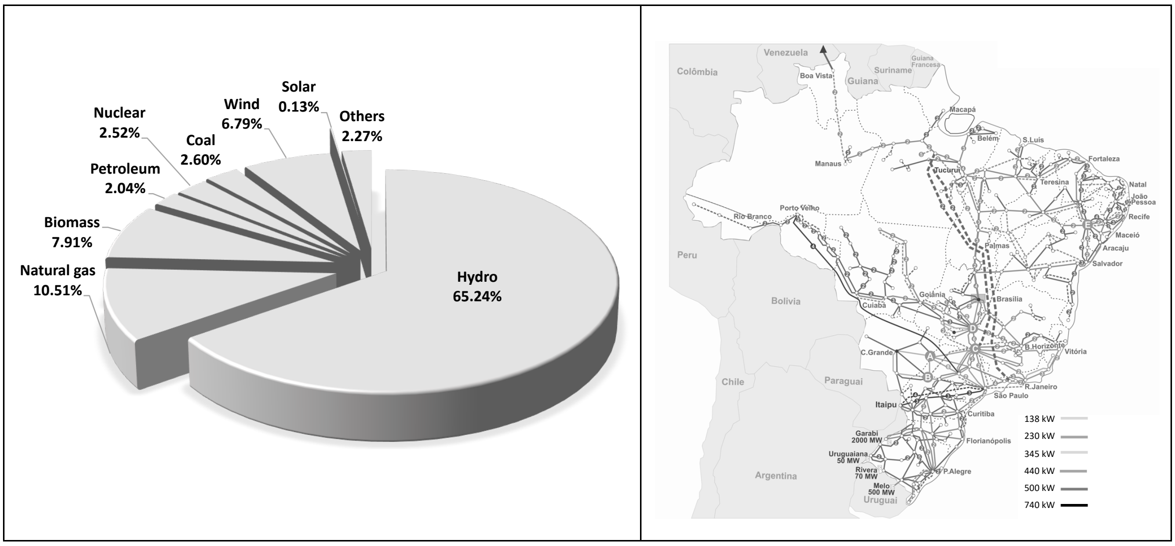

Fig. 1: Brazilian electric matrix (left) and the national interconnect electricity distribution grid - SIN (right)
source: EPE/BEN, 2018

Conflicts related to the multiple use of water and the climatic conditions that lead to rationing bring constant concerns about the vulnerability of hydroelectric plants. In addition, the country is approaching the exhaustion of its main hydrographic basins, which has led to the expansion of the sector to areas of great environmental and social concerns, such as the Amazon region. Water demand for power generation competes with water demand for agriculture, public urban supply, maintenance of biocapacity, and other purposes. This brings us to the intricate issue of the water-energy-food security nexus approach. In addition, the 10-Year Brazilian Energy Expansion Plan (PDE2026, 2018) anticipates increasing electricity consumption at an annual average rate of 3.7%, adding an additional demand of about 225 TWh by 2026.

Besides the need to meet the growing energy demand and to diversify energy sources, there are the Brazilian commitments to reduce emissions of greenhouse gases. Brazil should reduce 43% of the greenhouse gas

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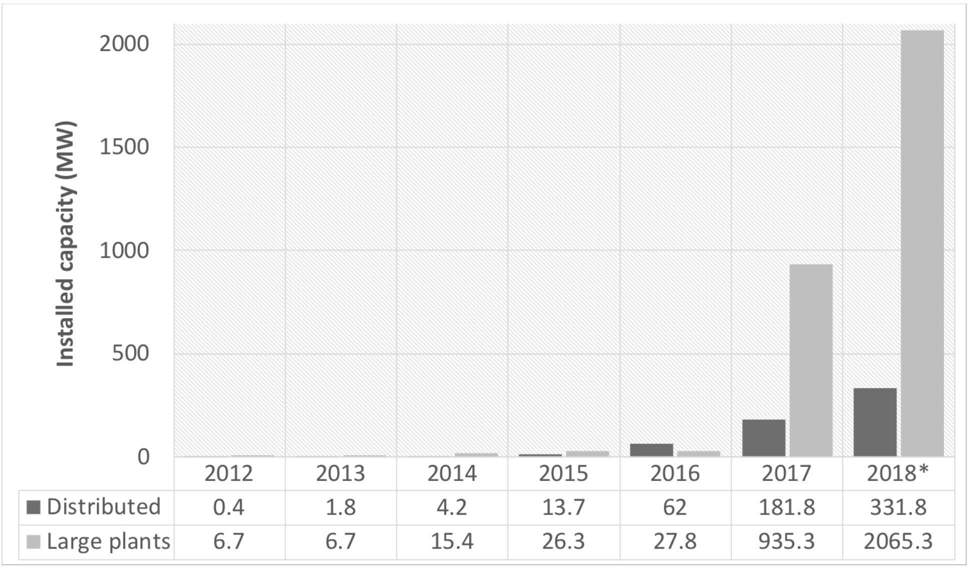
emissions by 2030 in relation to 2005 and achieve 45% renewable energy share in its energy matrix, including solar.

Brazil receives high levels of solar irradiation with low temporal and geographical variability. The annual average of global irradiation is between 1300 kWh/m^2 and 2200 kWh/m^2 throughout the Brazilian territory (Pereira, et al., 2017). Although the solar energy accounts for only 0.83% of the current national power supply (ANNEL, 2018), the solar technologies industries for power generation are growing fast in the country, at more than 250% increase in the last two years. The distributed microgeneration systems add up to 300 MW of installed power capacity with predominance of residential consumers (26,5%). The installed capacity in large photovoltaic power plants connected to the SIN, in turn, have recently exceeded the 1.5 GW. The country is expected to reach 2.4 GW at the end of 2018, accounting for the contribution of solar photovoltaic plants from the national reserve power auctions of 2014 and 2015 (EPE, 2018). Figure 2 depicts the annual growth of the installed PV capacity for distributed PV systems and large centralized PV plants.



	2012	2013	2014	2015	2016	2017	2018*
■ Distributed	0.4	1.8	4.2	13.7	62	181.8	331.8
■ Large plants	6.7	6.7	15.4	26.3	27.8	935.3	2065.3

Fig. 2: Brazilian PV cumulative installed capacity
source: ABSOLAR, 2018

The investment in large-scale intensive applications of solar technologies in Brazil is inhibited by insufficient or inadequate information on solar energy resource. Without reliable data, the potential investors tend to avoid the risk of solar project development activities. Barriers of knowledge and perception, once removed, are unlikely to return.

2. The Solar Energy Resource Assessment Model

In order to remove this information barrier, INPE/LABREN launched the Brazilian Atlas of Solar Energy (Pereira, et al., 2017). This work comprises 17 years of satellite data and a physical spectral model for solving the radiative transfer equation in the atmosphere, called BRASIL-SR (Martins & Pereira, 2006). This work has provided stakeholders and investors with good estimates of the various components of solar irradiation needed for solar energy projects. The model BRASIL-SR estimates the incoming solar irradiation based on the assumption that the solar radiation flux measured at the top of the atmosphere is linearly distributed between two extreme conditions of solar light transmittances: the clear sky (τ_{clear}) and totally cloudy sky (τ_{cloud}). These extreme transmittances are calculated by using a "two-stream" approximation scheme (Meador and Weaver,1980), for solving the radiative transfer equation. The model uses as input a normalized pixel-by-pixel digital data (l^i) provided by the geostationary satellite images, to evaluate the effective cloud coverage (C^i_{eff} defined by Equation 1:

$$\boldsymbol{C^i_{eff}} = \frac{l^i - l^i_{clear}}{l^i_{cloud} - l^i_{clear}} \qquad \text{(eq.1)}$$

The spatial resolution of the satellite images is 0.125 ° in latitude and 0.155 ° in longitude, corresponding to 12.5 km x 15.5 km at the lowest point until 2003. Thereafter, the resolution passes to 0.05 ° in latitude and 0.03 ° in longitude (3 km x 5 km), which also corresponds to the spatial resolution of the model output.The clear sky (l^{i}_{clear}) and cloudy sky (l^{i}_{cloud}) satellite readings are obtained from a monthly statistic for each satellite image timeframe.

The transmitance coefficients are obtained from the parameterization of the physical processes in the atmosphere. The atmospheric optical properties are parameterized from the meteorological variables of surface air temperature, relative humidity, atmospheric visibility and surface albedo. The temperature and relative humidity database were produced from the average values measured by automatic meteorological stations distributed all over Brazil and operated by the National Institute of Meteorology (INMET). Surface albedo values were obtained from DAAC-Langley products. The topography data was re-sampled from the GTOPO products, produced by EROS Data Center, with same horizontal resolution of the image of the GOES satellite used to obtain effective cloud cover ($\boldsymbol{C^{i}_{eff}}$). The horizontal visibility data (Costa, 2012) and the aerosol optical thickness data at 550 μm from MACC / ECMWF reanalysis was used to parametrize the aerosol transmitance (Costa *et. al*, 2015).

It is known that numerical models present limitations, which cause uncertainties that vary from region to region throughout the year. In order to evaluate such model uncertainties, the outputs were validated against surface data collected by pyranometers. This procedure employed more than 400 radiometric stations from the SONDA network <http://sonda.ccst.inpe.br/> and from the INMET automatic weather stations network <http://www.inmet.gov.br/portal/index.php?r=estacoes/estacoesautomaticas>, distributed throughout the nation.

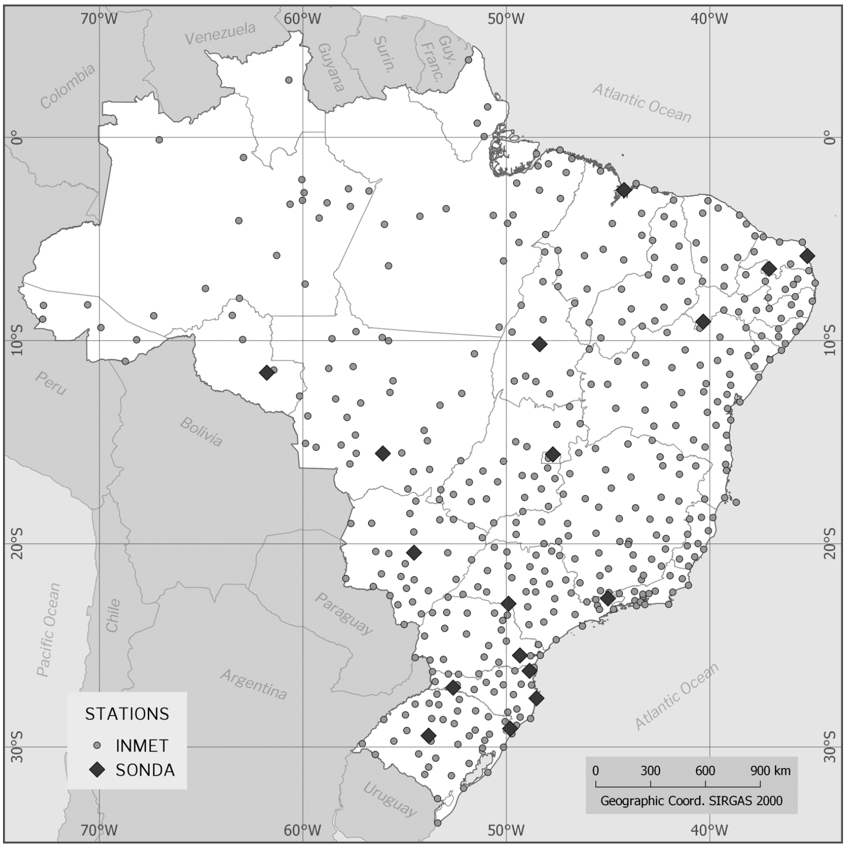


Fig. 3: Spatial distribution of ground data for global solar irradiation used to validate the model outputs – dots are INMET weather stations, and squares, are ground sites of the SONDA network.

This dense radiometric database also allowed us not only to spatially evaluate the accuracy of the numerical model in the estimates of daily irradiation on Brazil for each pixel/month of the year but also to minimize the model uncertainty through a post-processing procedure. To do this, a regionalized bias removal methodology was applied. This post-processing methodology consisted in adjusting the daily irradiation data, where the mean error (Bias) patterns for each month were statistically modeled using local spatial regression techniques, generating corrections that were applied to the modeled irradiation data. Figure 4 shows the relative systematic deviations between the untreated model outputs and the adjusted surface of bias. This surfaces of bias were obtained by a judicious procedure of bias interpolation, using as validation metrics independent samples (control) containing the best quality data from the SONDA network. This stage allowed a reduction of around 50% in the uncertainties of the numerical model outputs. From this figure it is possible to see that the North region presented the maximum positive bias during the austral summer (January) while the Northeast presented the maximum negative bias during winter (Junho). The large number of convective clouds in the Amazon region can explain this pattern during the austral summer when the ITCZ is shifted to the southern hemisphere. This condition causes a persistent overcast sky throughout the month, which precludes the correct determination of l^{i}_{clear}. On the other hand, during the winter, there is a persistence of clear days in the Brazilian Northeastern region, which results in a opposite situation, in which $\boldsymbol{C^{i}_{eff}}$ is also distorted by the difficulty of determining l^{i}_{cloud}. Both situations lead to inaccurate values of $\boldsymbol{C^{i}_{eff}}$ and as consequence, systematic deviations on the model outputs.

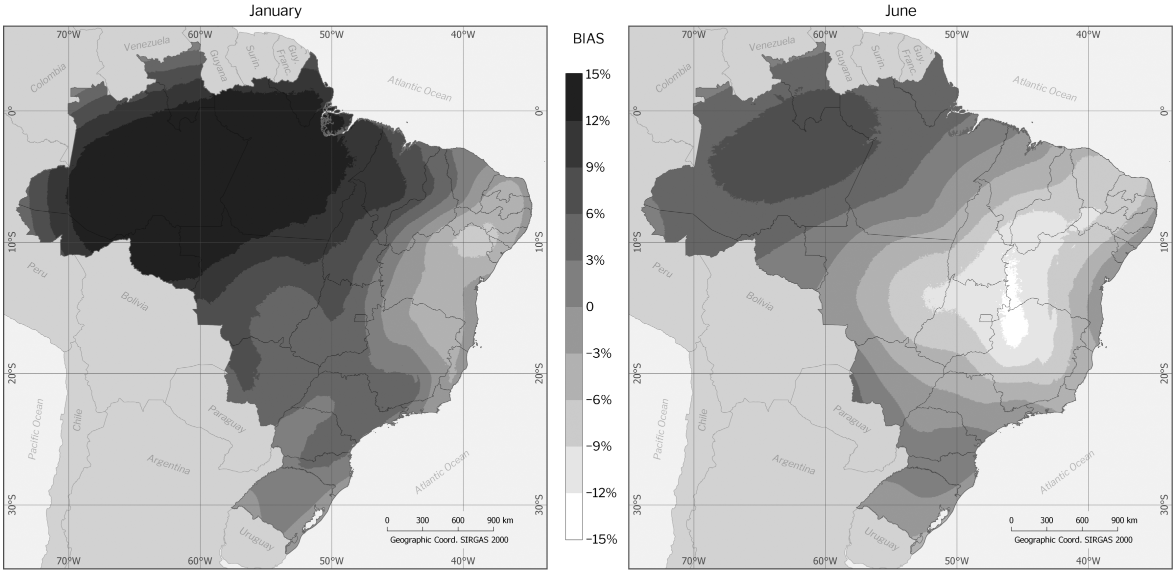


Fig. 4: Maps of the relative systematic deviations (Bias) of the raw output provided by the model BRASIL-SR, left: January and right: June.

From the final database, the Brazilian Southern and Southeastern regions presented the lowest relative bias deviation compared to the other regions, 0.1% of the annual solar irradiation average, while the Northeastern and the Midwestern regions exhibited the lowest relative root mean square error (RMSE) of 8,3%. The Northern region has shown the largest deviations, 9.7% for the relative RMSE and 0,6% for the relative bias deviation. Table 1 shows the benchmark result of the validation procedure.

Table 1: Benchmark parameters of Global horizontal irradiation for the model for each of the major geographic regions in Brazil:

Geographic Region	r	Bias (kWh/m^{2}· a)	Relative Bias (%)	RMSE (kWh/m^{2}·a)	Relative RMSE (%)	Annual Mean (kWh/m^{2}·a)
North	0.81	11	0.6	170	9.7	1761
Northeast	0.87	4.4	0.2	166	8.3	2001
Midwest	0.86	8.4	0.5	154	8.3	1855
Southeast	0.91	1.5	0.1	152	8.4	1807
South	0.98	-1.5	-0.1	144	8.9	1622

3. Solar irradiation mapping

Figure 5 shows the month-by-month global solar irradiation in Wh/m2.day, calculated for a tilted plan with an angle equal to de local latitude facing the North. Regarding the geographic distribution, the highest values of the surface solar irradiation occur mostly along a wide northeast-southwest band. The maximum values of solar irradiation occur mostly during winter time with monthly averages of about 6.9 kWh/m^2.day in the Northeastern region while the monthly minimum averages occur in the southern region, also in the southern winter of about 3.0 kWh / m^2. day.

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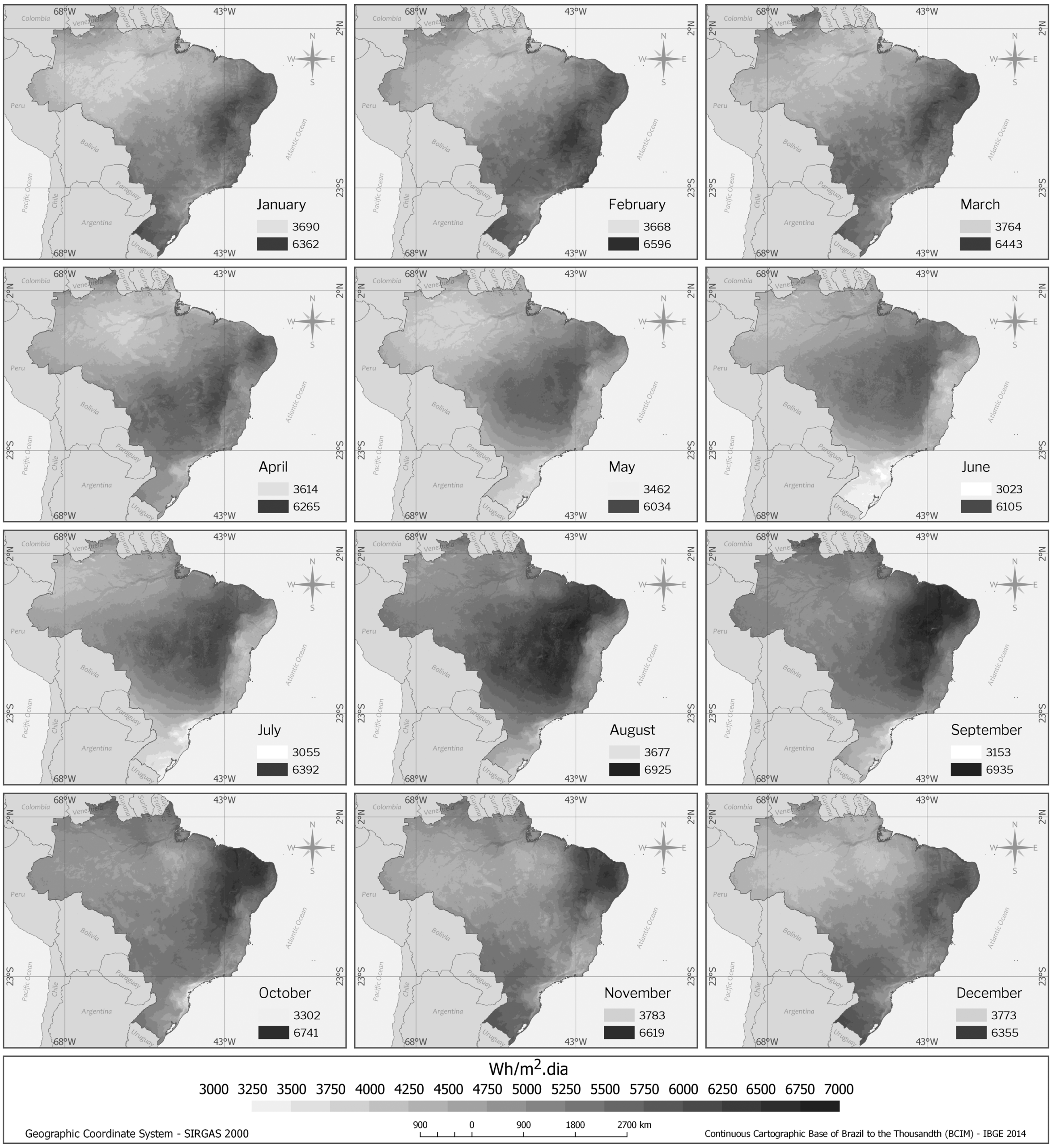

Fig. 5: Monthly maps for the mean surface solar global irradiation (Wh/m2.day) at the tilted plan equal to the local latitude angle.

Figure 6 shows the boxplot for the interannual variability of the surface solar irradiation for all Brazilian regions. The Northeastern region presents the lowest interannual variability, with extreme values between 5.39 and 5.59 kWh/m^2, and 50% of the annual averages are in the range between 5.43 and 5.50 kWh/m^2. In the South, 50% of the annual averages present values between 4.53 and 4.61 kWh/m^2, while in the Northern region the average annual values range between 4.61 and 4.69 kWh/m^2. The Southeastern region presented the highest interannual variability, with annual mean values between 4.97 and 5.11 kW/m^2 in 50% of the years between 2005 and 2015, although the extremes (4.95 and 5.23 kWh/m^2) present amplitude lower than that of the Southern Region.

Figure 7 shows the maximum annual energy yield (measured in kWh of energy generated per year for each kWp of installed photovoltaic power) throughout the country, both for large centralized plants and for distributed photovoltaic generation, integrated in roofs of households and commercial buildings. The annual average performance ratio of 80% was adopted to simplify the analysis and represents the performance of a well-designed and installed photovoltaic power generator and good quality equipment. The major cities and urban metropolitan regions are represented by dots which sizes are proportional to the population.

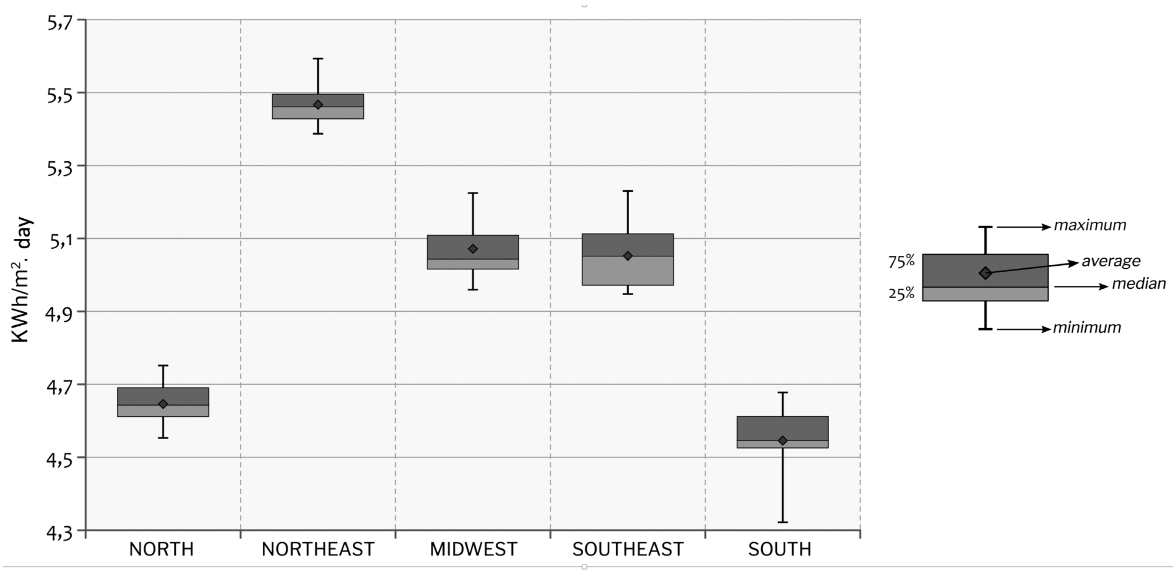

Fig. 6: Interannual variability of the annual mean of the surface solar irradiation for all Brazilian regions.

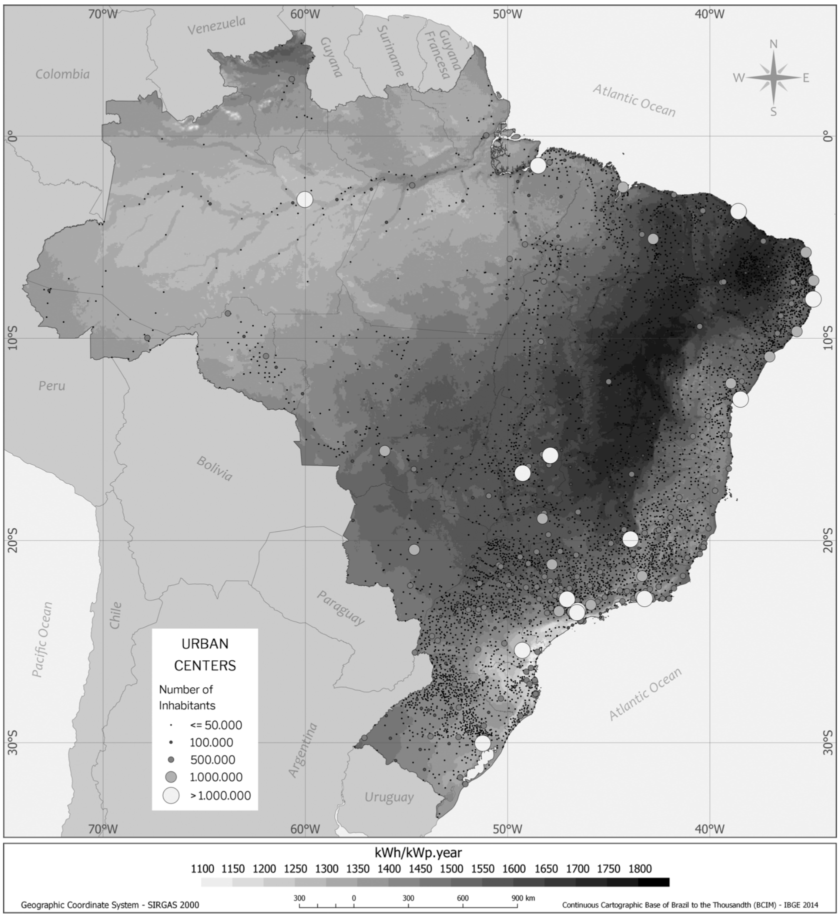

Fig. 7: Map of the PV yield in kWh/kWp. The round dots are the location of the major urban areas and their size is proportional to the number of inhabitants.

Figure 8 compares the variability of the monthly mean global horizontal irradiance in Brazil and some European countries. The comparison is made by box-plot diagram for monthly averages of daily solar irradiation. The height of the boxes is representative of the variability for the monthly average of the surface solar irradiation. The plot highlights the relatively high levels and the low variability of the surface solar irradiation in the Brazilian territory compared to some EU countries where PV technology is already settled. The Brazilian Northeastern region surpasses even countries of the Iberian Peninsula with much lower variability. The Southern region presents similar surface solar irradiation to these European countries, particularly in terms of the monthly variability. This is due to the higher latitudes of these countries and, therefore, greater differences in the duration of the day between seasons.

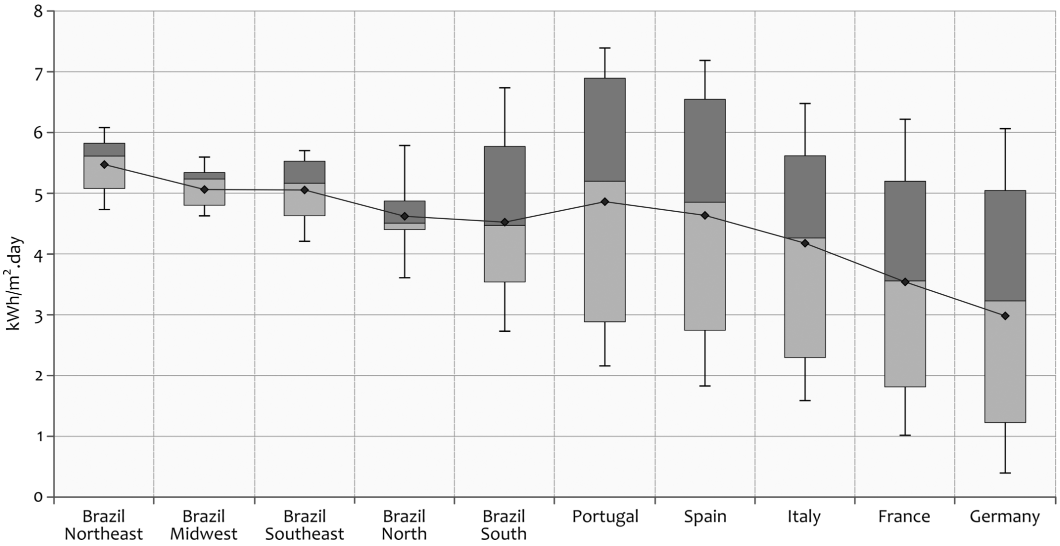

Fig. 8: Box-plot diagram for the PV potential in the all Brazilian macro-regions and some European countries where the solar energy market is well consolidated. Source: Pereira, 2017 and Šúri et al., 2007.

4. Conclusions

The Brazilian Northeastern region has the highest PV potential, presenting an average value of the global horizontal solar irradiation of 5.49 kWh/m^2.day and the direct normal component of 5.05 kWh/m^2.day. It is the region with the lowest interannual and intra-annual variability of the surface solar irradiation. The Southeastern and Midwestern regions present daily totals of the global horizontal irradiation close to 5.07 kWh/m^2.day. The mean global irradiance for latitude tilted plane in the in the Southeast of Brazil is of 5.26 kWh/m^2.day, while the Midwestern region is 5.20 kWh/m^2.day.

The relatively lower surface solar irradiation in the Northern region are justified by the typical climate characteristics of the region presenting frequent cloudiness, mainly during the austral summer when the ITCZ is shifted toward the South hemisphere. Thus, the average global irradiance in the horizontal and tilted planes has values close to those obtained for the Southern region and the direct normal irradiation is lower than all other regions of the country due to large diffuse solar irradiation.

Large-scale plants, typically installed on fixed-sloping metal structures or following the apparent trajectory of the Sun on one axis, have been mainly located in the Northeast, Midwest and some in the Southeast of Brazil. These regions have the highest average annual yields, as shown in Figure 7. To the extent that these areas and their energy transmission systems tend to saturate or require larger investments to accommodate increasing installed capacity, other regions of Brazil will be competitive, notably the Southern regions. Smaller distances to the key energy consumption centers and the large load of the National Interconnected System (SIN) favor the displacement of target areas for solar power projects. Furthermore, the greater availability of connection points to the SIN minimizes the need for new transmission lines. There are excellent annual levels of irradiation in the western areas of the states of São Paulo, Paraná, Santa Catarina and Rio Grande do Sul during the summer months, and in some areas the values may be similar to the monthly averages of several locations where large photovoltaic are being installed.

This work highlighted the high level and low variability of solar irradiation in the Brazilian territory compared to countries where PV technology is well established. In addition to the abundance of radiant energy from the Sun, the country has an enormous extension of degraded areas, or of low economic value, for the deployment of power generation projects using solar technology, enhanced by an electric energy distribution system that covers practically the entire national territory connected to several large hydroelectric plants. It brings the possibility of connecting PV power plants to the energy distribution system practically all over the country, with the exception of the North region. Notwithstanding these advantages, another great differential is based on the possibility of socioeconomic transformation of the low-income population of the Northeastern semi-arid region. Micro and mini distributed PV power generation, solar water desalination and water pumping, can become reality through new public policies, promoting regional economic development and social inclusion.

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