Periódico Eletrônico "Fórum Ambiental da Alta Paulista"
Electronic Journal "Environmental Forum of Alta Paulista"

ISSN 1980-0827 – Volume 20, Number 1, Year 2024

Climate Change and its Impacts on Photovoltaic Systems in each State of Brazil

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ABSTRACT

Audacious plans are being implemented all over the world to mitigate climate change. Such plans require significant increases in the use of renewable and clean energy, making systems more vulnerable, as they are also impacted by climate change. This article seeks to elucidate future climate effects that may affect residential photovoltaic (PV) systems. In this article, the conditions of existing residential photovoltaic systems in Brazil are evaluated, representing a total of 818,149 installations, meaning 78% of all types of installations (commercial, rural, industrial, residential...). Here we also analyze the performance of the facilities for 59 years of meteorological data (1961 – 2020) and project forecasts of future climates for up to 100 years. It was found in the results that all Brazilian states already suffer large efficiency losses due to the high environmental temperature, which are gradually increasing, year after year, reaching a maximum average annual increase of more than 5 ºC in the north of the country. Even with perspectives of reduction in efficiency in this scenario of PV electricity generation, it is unlikely that such climate changes will threaten this sector in Brazil, as there is still a strong potential for use. The main reason for these predictions of increases in solar incidence is due to reductions in precipitation in all regions in the medium and long term.

Keywords: Climate changes. Temperature increase. Photovoltaic Systems. Efficiency. Future Projections.

1 INTRODUCTION

With the growing world population along with the greater demands for electricity, concerns about global warming arise from climate change and human activities that are only increasing. Renewable energies are increasingly gaining space, but the world economy still depends heavily on conventional fuels to meet its demands. However, the decrease in fossil fuel reserves and ecological problems (IBRAHIM et al. 2011) make the use of renewable energy increasingly inevitable (DAS, KALITA and ROY, 2018). One of them is photovoltaic (PV) solar energy, which is considered an inexhaustible source of energy if one considers terrestrial time and because it does not have moving parts in its operation. This form of generation is increasingly increasing the positive points for its choice, such as greater efficiency compared to other renewable sources (PARIDA, INIYAN and GOIC, 2011), but still suffer losses due to climatic factors such as temperature increase and irradiance (COTFAS; COTFAS and MACHIDON, 2018). Another important issue is the dependence of solar energy on local climatic conditions, which makes photovoltaic production vulnerable to climate change and natural climate variability (Ravestein et al. 2018).

The IPCC (Intergovernmental Panel on Climate Change), formed in 1988 by the United Nations Environment Program (UNEP) and the World Meteorological Organization (WMO), is considered the main scientific body responsible for assessing climate change and its environmental and socioeconomic impacts. According to the IPCC, climate change includes statistically significant changes in the most representative climate variables, such as precipitation, temperature, winds and others. Natural processes, external forces or even human actions in land use and atmospheric composition (IPCC, 2013) can cause these changes.

To avoid dangerous anthropogenic interference with the climate system, the Paris Agreement set a target to keep global temperature rise below 2 °C and pursue efforts to limit it significantly to 1.5 °C above the pre-industrial level. The project establishes that Brazil will neutralize 100% of its emissions by the year 2050, in accordance with the National Long-Term Strategy (United Nations Framework Convention on Climate Change 2015).

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The production of energy from photovoltaic systems is quite unpredictable due to local climatic conditions and their changes. Even so, it is possible to make a long-term projection to know about the conditions of environmental temperatures and their uncertainties in each location. This is due to climate changes that do not occur uniformly everywhere, each state will always have a different impact and consequently a particular capacity of generated electrical energy.

It is known that solar resources are not stable over time and undergo substantial changes like those that occurred in the 21st century (Wild et al. 2015, Huber et al. 2016). Therefore, the potential impacts of climate change must be considered in detail when planning a long-term management of photovoltaic solar energy (Soares et al. 2019, Poddar et al. 2021, Danso et al. 2022). For photovoltaic cells for terrestrial use without concentration of solar energy, the I-V curve is measured under standard test conditions: irradiance of 1000 W/m², solar spectrum AM 1.5 and photovoltaic cell temperature of 25 ºC (PINHO and GALDINO 2014).

In the study by (BENGHANEM, AL-MASHRAQI and DAFFALLAH, 2016) temperatures of photovoltaic cells were found that varied in most locations from 0 ºC to 60 ºC, with places where the lower limit of the working temperature was below -20 ºC and a limit higher than 80 °C in semi-arid areas. There are applications that may still exceed these values, such as space applications or in extreme locations.

According to (COTFAS; COTFAS and MACHIDON, 2018), in a study with various technologies of photovoltaic cells and analyzes of the influence of temperature between 25 ºC and 87 ºC at maximum power, all showed an influence that varied from 0.14% to 0.47% every 1 °C if the temperature exceeds 25°C. This study shows that, regardless of the technology currently available on the market, PV panels are still impacted by temperature increases, resulting in significant reductions in the maximum power generated and, consequently, in increased investments.

This article aims to provide an overview of existing residential photovoltaic systems in Brazil and project future changes to their photovoltaic potential based on a set of climate simulations. This is an initial attempt at a comprehensive investigation of changes in photovoltaic potential in Brazil, taking into account the possibility of a warmer future. From these analyses, this study can be replicated worldwide following the proposed methodology and if there are meteorological data in the study sites.

This article is organized as follows: section 2 presents the materials and methods used. Section 3 provides the results and discussions. Section 4 gathers the conclusions found.

2 MATERIALS AND METHODS

The central points explored in this work aim to: 1) analyze the scenario in Brazil in relation to existing residential photovoltaic systems; 2) project future scenarios in relation to the average annual temperature of each Brazilian state and 3) evaluate the possible losses resulting from these changes in photovoltaic systems.

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2.1 Climate Data and Existing Photovoltaic Systems in Brazil

For this article, data were gathered from all photovoltaic systems in Brazil provided by the Law of Access to Information - LAI (LAI, 2022), focusing on current residential installations. It was observed that by the month of September 2022 there were a total of 1,048,574 photovoltaic systems regularized and registered throughout Brazil and, in the residential category, a total of 818,149 generating units, which represents 78% of the installations. Faced with this large category, it was decided to analyze each state of Brazil individually in terms of how climate change will affect electricity generation in the coming years. Furthermore, with data from the National Institute of Meteorology – INMET, 27 meteorological stations spread across Brazil were selected, one in each state, totaling 27 stations, which represent the 26 states of Brazil plus the Federal District, as shown in Table 1. The period used for this was based on data obtained from 1961 to 2020, totaling up to 59 years of meteorological data, with information taking into account maximum and minimum average ambient temperatures, precipitation, solar insolation and wind speed (INMET, 2022).

The locations chosen for Table 1 were determined by their greater amount of data available and with the lowest possible interruptions, compared to other locations. In the absence of data (missing), it was decided not to fill them in statistically, so as not to interfere in the analysis. According to [Gaspareto et al. 2021], such methods have their weaknesses and can bring results that are different from what the sampling reality was, even when choosing more sophisticated methods to fill in the missing data, such as the random forest, or extremely traditional methods in the area, such as linear regression. The time window was limited to up to 59 years of data, as in several locations there had been no meteorological stations since 1961. For these locations, data from the year they were installed were used. These data are gathered in Table 2, which shows the number of residential photovoltaic panels used in Brazil and their respective brands.

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Table 1: Locations from which data from meteorological stations were acquired and their respective historical periods.

City	State	Latitude (S)	Longitude (W)	Altitude (m)	Period
Rio Branco	AC	-9,95	-67,86	160,71	1970-2020
Água Branca	AL	-9,26	-37,93	603,42	1974-2020
Manaus	AM	-3,10	-60,01	61,25	1961-2020
Macapá	AP	-0,04	-51,11	12,8	1968-2020
Barreiras	BA	-12,15	-45,00	447,51	1961-2020
Fortaleza	CE	-3,81	-38,53	29,89	1961-2020
Brasília	DF	-15,78	-47,923	1161,42	1962-2020
Vitoria	ES	-20,31	-40,31	36,2	1961-2020
Catalão	GO	-18,170	-47,95	857,98	1961-2020
São Luís	MA	-2,52	-44,21	32,58	1971-2020
Belo Horizonte	MG	-19,93	-43,95	915,47	1961-2020
Paranaíba	MS	-19,66	-51,19	429,62	1972-2020
Cuiabá	MT	-15,62	-56,10	157,7	1961-2020
Itaituba	PA	-4,27	-55,99	24,5	1966-2020
Monteiro	PB	-7,89	-37,12	606,41	1963-2020
Cabrobó	PE	-8,50	-39,31	342,78	1965-2020
Teresina	PI	-5,03	-42,80	75,73	1961-2020
Londrina	PR	-23,32	-51,14	566	1961-2020
Campus	RJ	-21,74	-41,33	11,2	1961-2020
Apodi	RN	-5,62	-37,81	131,37	1963-2020
Caracaraí	RR	1,83	-6,11	51,99	1971-2020
Santa Maria	RS	-29,72	-53,72	103,1	1961-2020
Chapecó	SC	-27,13	-52,66	654	1974-2016
Própria	SE	-10,21	-36,84	18,46	1964-2020
São Paulo	SP	-23,49	-46,62	785,16	1961-2020
Porto Nacional	TO	-10,71	-48,40	243,28	1961-2020

Table 2: Number of residential systems that use a certain brand of photovoltaic panels in Brazil and their respective percentages.

Trade Mark	Amount	Percentage of total (%)
Canadian Solar	138960	16,98
Jinko Solar	99378	12,14
Byd	88004	10,75
Risen Solar Technology	84014	10,26
Trina Solar	64900	7,93
DAH Solar	52574	6,42
Intelbras	19063	2,33
Others (smaller quantities)	271256	33,15
Total	818149	100

2.2 Photovoltaic Losses by Temperature

The photovoltaic energy production of a site depends mainly on two factors: its photovoltaic potential (*PVpot(t)*) and the installed capacity. The acronym *PVpot(t)* is a dimensionless measure of the performance of photovoltaic cells in relation to their rated power capacity under real environmental conditions. Therefore, the *PVpot* is multiplied by the installed photovoltaic capacity of nominal power that can provide an instantaneous generation of photovoltaic energy [Jerez et al. 2015].

A $PV_{pot}(t)$ mainly involves the amount of resources (*RSDS*) and possible effects of other atmospheric variables on photovoltaic efficiency in cells, which decrease with increasing temperature [RADZIEMSKA, 2003]. According to [MAVROMATAKIS, 2010], the $PV_{pot}(t)$ can be expressed as:

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$$PV_{pot}(t) = P_R(t)\frac{RSDS(t)}{RSDS_{STC}} \tag{1}$$

where *STC* refers to standard test conditions ($RSDS_{STC} = 1.000\ W/m^2$)

The nominal capacity of a photovoltaic device is determined by the measured energy output and P_R is the so-called performance ratio, which is formulated to take into account temperature variations that affect the efficiency of photovoltaic cells, such as:

$$P_R(t) = 1 + \gamma[T_{cell}(t) - T_{STC}] \tag{2}$$

where T is the cell temperature, T_{STC} = 25 °C and γ is considered here as -0,005 °C^{-1}, this being a typical response of monocrystalline silicon solar panels [Jerez et al. 2015].

Finally, the cell temperature *T* is modeled considering the effects of Surface Air Temperature (*TAS*), Surface Descending Solar Radiation under full sky conditions (*RSDS*) and Surface Wind Speed (*VWS*) impinging on it as:

$$T_{cell}(t) = C_1 + C_2TAS(t) + C_3RSDS(t) + C_4VWS(t) \tag{3}$$

where C_1 = 4.3 °C, C_2 = 0,943, C_3 = 0.028 °C m^{2}W^{-1} and C_4 = −1.528 °C sm^{-1} according to referece [CHENNI et al. 2007].

Therefore, if environmental conditions such as *RSDS*, *TAS* e *VWS* correspond to *STCs*, the $PVpot$ will be equal to 1 and the photovoltaic energy production will reach the nominal value. If T_{cell} is higher than 25 °C and/or *RSDS* less than 1.000 W/m^2, the $PVpot$ will be less than unity and the PV output power will be less than the module's rated power [JEREZ et al. 2015].

The changes induced by TAS in $PVpot(t)$ is estimated as follows:

$$\Delta TASinduced\ PV_{pot}(t) = \left(\frac{\alpha_3 RSDS(t) * \Delta TAS}{PV_{pot\ Historical}mean}\right) * 100 \tag{4}$$

where α_3 = -4.715 x 10^{-6} expressed in percentage.

Photovoltaic modules lose voltage when temperature increases, but gain a little current, in the Temperature Coefficient (P_{max}), which translates the percentage of loss in the module power when exceeding each degree Celsius above 25 ºC (temperature of the standard condition "STC").

Below is an example using data from a datasheet of a conventional monocrystalline photovoltaic plate: Nominal Module Operating Temperature (*NMOP*) = 42 ºC; Temperature Coefficient (*Pmax*) = - 0.37 %/ºC e *TAS* = 25 ºC. With these data, it is possible to calculate the results of an example of the percentage of efficiency loss in the module with formulas (5) and (6).

$$(\Delta t) = NMOT - TAS \tag{5}$$

$$(\%) =.\ \Delta t \text{ x Coef. de Temp. } (P_{max}) \tag{6}$$

where (Δt) is the temperature difference and (%) is the percentage loss of power due to temperature.

In the case of this example 1:

$$42\ °C - 25\ °C = 17\ °C \tag{7}$$

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$$17\ °C \times 0{,}37\ \%/°C = 6{,}29\ \% \qquad (8)$$

The maximum power of the module described above when its temperature is 42 ºC (for an ambient temperature of 25 ºC), will be on average 6.29% below that informed in the technical sheet (considering that the radiation is constant at 1000 W/m²). Following the model thus analyzed, the module with a nominal power of 400 Wp under these conditions will have a power of around 374.84 Wp, relative to the loss of efficiency due to the ambient temperature. However, real situations in Brazil make module and ambient temperatures far exceed these values, usually resulting in losses of approximately 15%.

To calculate the losses due to temperature, data from the datasheet of 6 brands of monocrystalline silicon photovoltaic panels, the most used throughout Brazil, were used, as shown in Table 3. From the information above, an average was made for the temperature coefficient (*Pmax*) in relation to each degree Celsius, having as reference the 25 ºC of the *STC* and its operating temperatures. An average temperature coefficient was found (*Pmax*) = -0.35 %/ºC and an operating temperature of 44 ºC ± 2. These data are used to make a perspective regarding the losses found in each studied location and their future projections.

Table 3: Datasheet of some monocrystalline photovoltaic panels most used in Brazil.

Trade Mark	Model	Power (W)	Temperature Coefficient of *Pmax*	($NMOP$)
Byd	MGK-36 MONOFACIAL 425W - 455W	425-455	-0.38 %/°C	45 ºC ± 2
Canadian	CS3W-445|450|455|460|465|470MS	445-470	-0.34 %/°C	41 ºC ± 3
Jinko	JKM440M-6TL4-V	440	-0.35 %/°C	45 ºC ± 2
Trina	TSM-DE18M	480-510	-0.34 %/°C	43 ºC ± 2
Risen	RSM150-8-480M-505M	480-505	-0.36 %/°C	44 ºC ± 2
DAH	DHM-66X10-475 ~ 505W	475-505	-0.35 %/°C	45 ºC ± 2

2.3 Future Projections

To analyze the impact of climate change on the durability of photovoltaic panels, historical climate data for each Brazilian state was used individually. The intention is thus to build a projection for future scenarios through a linear regression considering that the current technologies used for photovoltaic panels predict a useful life of approximately 25 years. Future time windows were built every 25 years to demonstrate the climate scenario in relation to the average annual ambient temperature for the years 2045, 2070, 2095 and 2120, thus totaling 100 years of projection. As each technology reacts differently in relation to temperatures, a certain future technology was chosen that presents better results in relation to another and that could analyze how the temperatures will be in each location in each time window. With this, it is verified whether it is advantageous to replace the technologies employed. Currently, the most used worldwide is Monocrystalline Silicon (AL-WAELI et al. 2016).

Several studies have been devoted to assessing the impacts of climate change on future photovoltaic potential based on dynamically reduced projections from other regions, such as Europe (Jerez et al 2015), Africa (Bichet et al 2019, Sawadogo et al 2021), Australia (Poddar et al 2021) and China (Park et al 2022, Wu et al 2022). In this direction, a study is still lacking for the change in the photovoltaic potential of all of Brazil on a regional scale. It should be taken into account that most of the current studies are based on projections of the global

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climate model (GCM), which do not reliably capture climate characteristics on a regional scale. Therefore, these studies may lead to a less reliable projection for future changes (Liang et al. 2008, You et al 2022). For this reason, this article makes a difference for an individual analysis of each region of Brazil, significantly increasing the reliability of forecasts and even being able to be replicated worldwide.

The projections of the PBMC (Brazilian Panel on Climate Change) for Brazil are for gradual increases of 1 to 6 °C in ambient temperature by the year 2100, compared to those recorded in the 20th century (PBMC, 2012). Table 4 shows forecasts of temperature increases for each Brazilian biome, according to the PBMC until 2100.

The increases shown in Table 4 will have a direct impact on all the country's fauna and flora and, together with these differences, reductions in the rainfall cycles between the biomes are expected by 2100, which vary from 35 to 50%. For photovoltaic systems, according to Marques, Pereira and Assis (2000), on a cloudy day and due to rain, the intensity of solar radiation reaching a module will be lower, and consequently there will be a reduction in energy generation. So, the smaller the amount of rainfall, the greater the solar incidence on the module, which will therefore have a greater energy potential.

Table 4: Projection of temperatures for each Brazilian biome up to 2100.

Biome		Period		
		Up to 2040	2041-2070	Up to 2040
Amazônia		1 a 1,5 ºC	3 a 3,5 ºC	5 a 6 ºC
Caatinga		0,5 a 1 ºC	1,5 a 2,5 ºC	3,5 a 4,5 ºC
Cerrado				5 a 5,5 ºC
Pantanal				3,5 a 4,5 ºC
Pampa		Até 1 ºC	1 a 1,5 ºC	2,5 a 3,5ºC
Mata Atlântica	- Noroeste	0,5 a 1 ºC	2 a 3 ºC	3 a 4 ºC
	- Sul e Sudoeste	0,5 a 1 ºC	1,5 a 2 ºC	2,5 a 3 ºC

Source: PBMC, 2012.

The Brazilian areas most vulnerable to climate change involve the Amazon and the Northeast (Guimarães et al. 2016). In addition, the Brazilian northeast is considered more vulnerable because conditions of increased temperature and changes in precipitation can transform some areas of the territory into arid regions, as it is the most populated semi-arid region in the world (Nóbrega, 2016).

2.4 Linear Regression and R^2

Linear regression has long played an important role in weather and climate forecasting, both for empirical forecasting models and in the statistical post-processing of results from physics-based forecasting models [TIPPETT, DELSOLE and BARNSTON 2014]. The linear approach presented in this section is an equation to estimate the conditional (expected value) of a variable y, given the values of some other variables x. To estimate the expected value, an equation is used, which determines the relationship between both variables.

$$\hat{y}_i = \propto + \beta X_i + \varepsilon_i \tag{9}$$

where ($\hat{y}_i$) is the explained (dependent) variable representing what model will predict better given a X_i; (α) is a constant, which represents the intersection of the straight line with the

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vertical axis; (β)represents the slope (angular coefficient) in relation to the explanatory variable; (X_i) is explanatory variable (independent) and (ε_i) represents all residual factors plus possible measurement errors.

The performance of the models was verified using the following statistical measure: coefficient of determination (R^2). One way to calculate R^2 is through summation of the total squares, residuals and explained (SQT, SQR and SQE):

$$SQT = \sum_{i=1}^{n}\left(Y_i - \bar{Y}\right)^2 = \sum_{i=1}^{n} Y_i^2 - \frac{(\sum Y_i)^2}{n} \tag{10}$$

SQT is the sum of the total squares; n the number of observations; Y_i the observed value; and Y_i is the average of observations. Equation 11 then gives the summation of the difference squares between the mean and each observed Y_i value.

$$SQR = \sum_{i=1}^{n}\left(Y_i - Y_i\right)^2 \tag{11}$$

SQR is the sum of the squares of the residuals, which calculates the unexplained part of the model, and $\widehat{Y_i}$ is the estimated value (forecast) of Y_i.

$$SQE = \sum_{i=1}^{n}\left(Y_i - \bar{Y}\right)^2 = \hat{\beta}^2 * \sum_{i=1}^{n}\left(X - \bar{X}\right)^2 = \hat{\beta}^2 * S_{xx} \tag{12}$$

SQE is the sum of explained squares, which indicates the difference between the mean of the observations and the estimated value for each observation, and adds the respective squares. Thus, the smaller the difference, the greater explanatory power the model has.

As R^2 is the percentage that the model ($\alpha + \beta * X_i$) evaluates the total variation (Y), $R^2 = SQE / SQT$. As $SQT = SQE + SQR$, one can also calculate R^2 as follows:

$$R^2 = \frac{SQE}{SQT} = 1 - \frac{SQR}{SQT} \tag{13}$$

The regression method was used to find a characteristic curve in relation to the data found regarding the ambient temperature of each location studied. With this curve, it was possible to make a more realistic future projection in this scenario. This method can be considered simple, but very accurate when analyzing coefficients R^2. The closer the results are to unity, the more significance and reliability they will have in future projections using equations 9 and 13.

With the methods presented in this article, the proposed methodology for forecasting PV generation can be replicated worldwide, requiring only climate information of the desired location taking into account local characteristics.

3 Results and Discussions

In terms of the number of photovoltaic panels installed in Brazil, there are a total of 43,994,242, and in the residential category a total of 18,088,813 panels, despite representing 78% of the installed systems. The difference is due to commercial systems and solar plants having a large number of plates in a single installation (LAI, 2022). Figure 1 shows the distribution of residential photovoltaic panels by state and Figure 2 shows the total number of inverters used.

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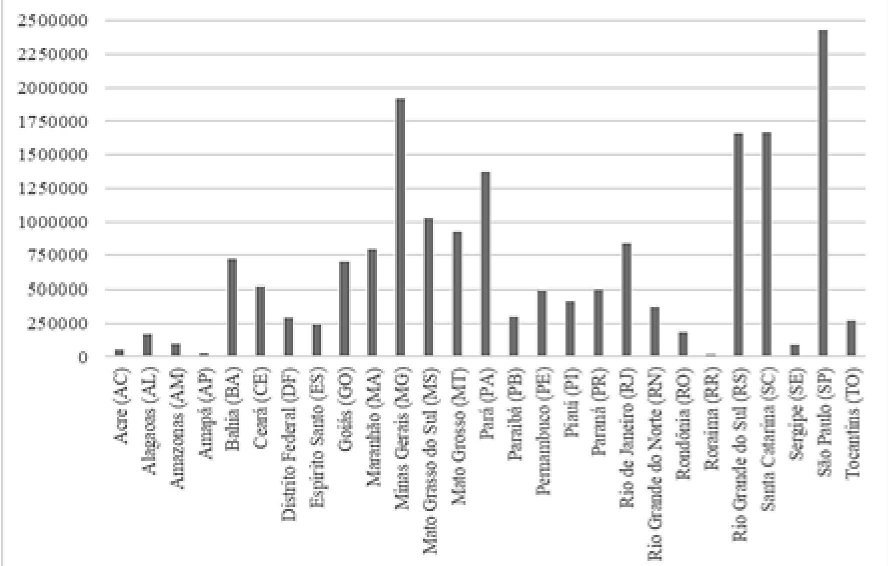
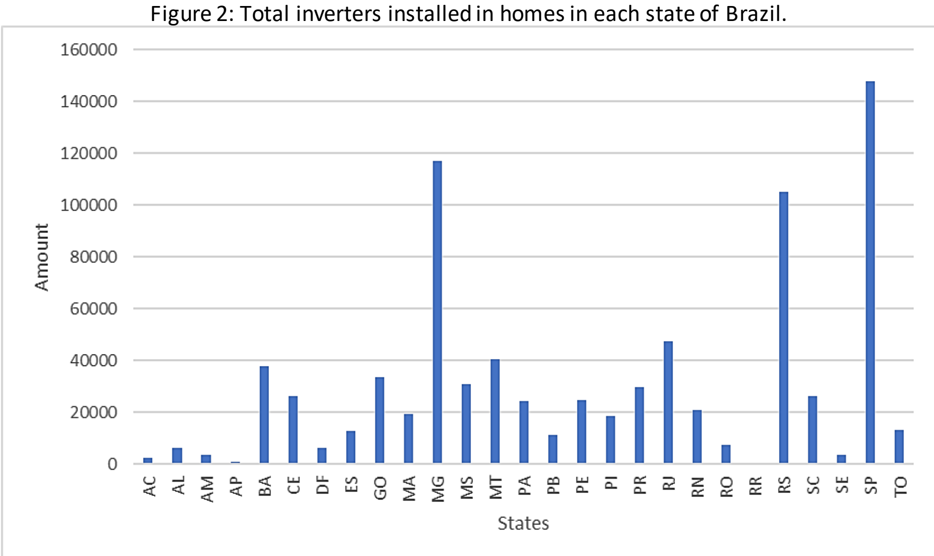
Figure 1: Total residential photovoltaic panels installed in each state in Brazil.



The state with the largest number of residential photovoltaic panels is São Paulo (SP), followed by Minas Gerais (MG), Rio Grande do Sul (RS) and Santa Catarina (SC). However, the state with the highest installed capacity and license plates in all categories is Minas Gerais. These results show the importance of this work when analyzing mainly residential systems, which cover a greater number of installations and, consequently, this study could help more people with future predictions and clarify doubts about photovoltaic installations.

Figure 2: Total inverters installed in homes in each state of Brazil.



It can be seen in Figure 2 that Santa Catarina (SC) is no longer among the 4 largest quantities of power inverters because there is a very large number of inverter models available on the market with even more varied powers. It is observed that in this region, higher power inverters were chosen and, therefore, in smaller quantities. In all of Brazil in photovoltaic

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residential installations there are a little less than one million power inverters to date.

Figure 3 shows the distribution of average annual temperatures in the state of Goiás (GO) from 1961 to 2020, clearly proving that temperatures are rising linearly over time, as in other locations. The use of this linear regression generated a discovery and a much more accurate R^2 for future projections that can be seen in Figure 3, demonstrating how this work can contribute to other studies. This refers more specifically to the benefits of new projects and increased knowledge related to future scenarios for PV stations. The results obtained on climate change prove the importance of works like the ones in this article to a better understanding of future scenarios.

Table 5 shows a projection for the increases in temperatures of each location analyzed in their respective time windows and, at the end, the coefficient of determination (R^2) to demonstrate how much the model presented here fits the samples of data collected.

Temperature increases greater than 5 ºC were found for 100 years from now, thus showing that the impact of climate change will affect each location differently. In the southern states of Brazil where average annual temperatures are lower, changes are less significant, but impacts on biodiversity can be even greater. This is due to the climate having negative temperatures at certain times of the year, which may not occur in the future.

Figure 3: Dispersion of mean annual temperatures in Goiás (GO) from 1961 to 2020 and its trend line.

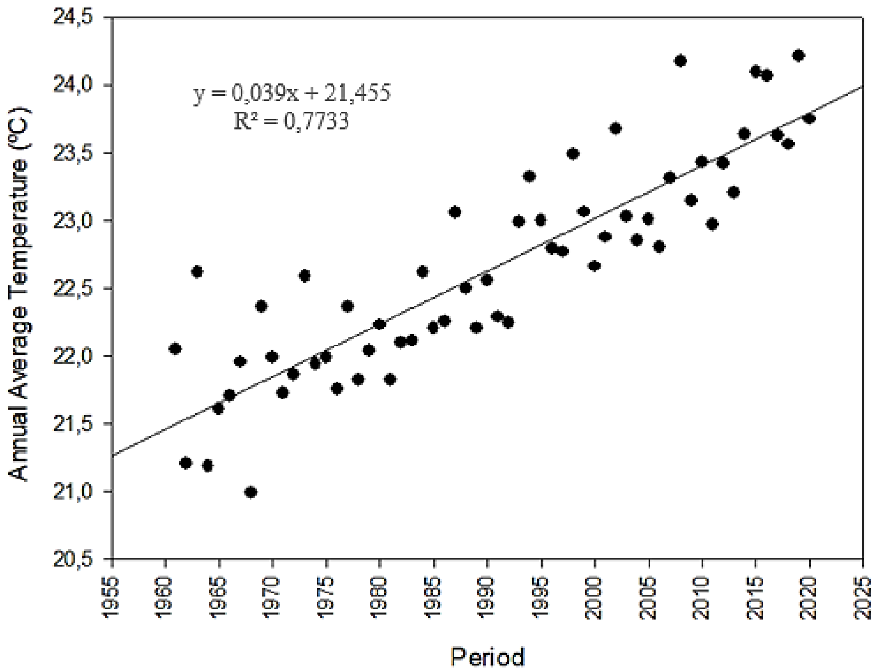

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Table 5: Projection of annual average temperature increases in relation to each city/state studied

City	State	25 years	50 years	75 years	100 years	R^2
Guarapuava	PR	0,77	1,58	2,39	3,20	0,60
São Paulo	SP	0,95	1,91	2,86	3,82	0,72
Brasília	DF	0,88	1,59	2,30	3,01	0,64
Macapá	AP	0,80	1,51	2,21	2,92	0,71
Apodi	RN	0,40	0,82	1,24	1,66	0,17
Santa Maria	RS	0,45	0,77	1,09	1,41	0,20
Cuiabá	MT	0,53	1,08	1,63	2,18	0,45
Água Branca	AL	0,30	0,61	0,92	1,23	0,15
Fortaleza	CE	0,36	0,74	1,12	1,50	0,43
Cabrobó	PE	0,70	1,43	2,15	2,88	0,51
Teresina	PI	0,29	0,57	0,86	1,15	0,09
Manaus	AM	0,61	1,25	1,89	2,52	0,54
Itaituba	PA	1,23	2,50	3,78	5,06	0,77
Campus	RJ	0,51	1,04	1,58	2,11	0,53
Barreiras	BA	0,8	1,63	2,46	3,30	0,61
São Luiz	MA	0,90	1,80	2,71	3,61	0,68
Monteiro	PB	0,65	1,32	2,00	2,67	0,59
Própria	SE	0,74	1,50	2,27	3,04	0,55
Vitória	ES	0,54	1,09	1,65	2,21	0,48
Belo Horizonte	MG	0,67	1,37	1,93	2,77	0,58
Catalão	GO	0,94	1,91	2,89	3,86	0,77
Chapecó	SC	0,56	1,12	1,68	2,24	0,28
Rio Branco	AC	0,20	0,75	1,30	1,85	0,50
Caracaraí	RR	0,69	1,47	2,26	3,04	0,49
Paranaíba	MS	0,86	1,72	2,58	3,44	0,56
Porto Nacional	TO	0,99	2,00	3,03	4,05	0,73
Porto Velho	RO	*	*	*	*	*

* Many missing data, making an analysis impossible and the non-existence of another meteorological station in the indicated state.

In Figure 4, one can see the progressive temperature changes in each state. For a better interpretation, the state of Pará (PA) will be the most impacted; consequently will have greater losses in photovoltaic systems due to the increase in temperatures.

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Figure 4: Increase in average annual temperature in each Brazilian state.

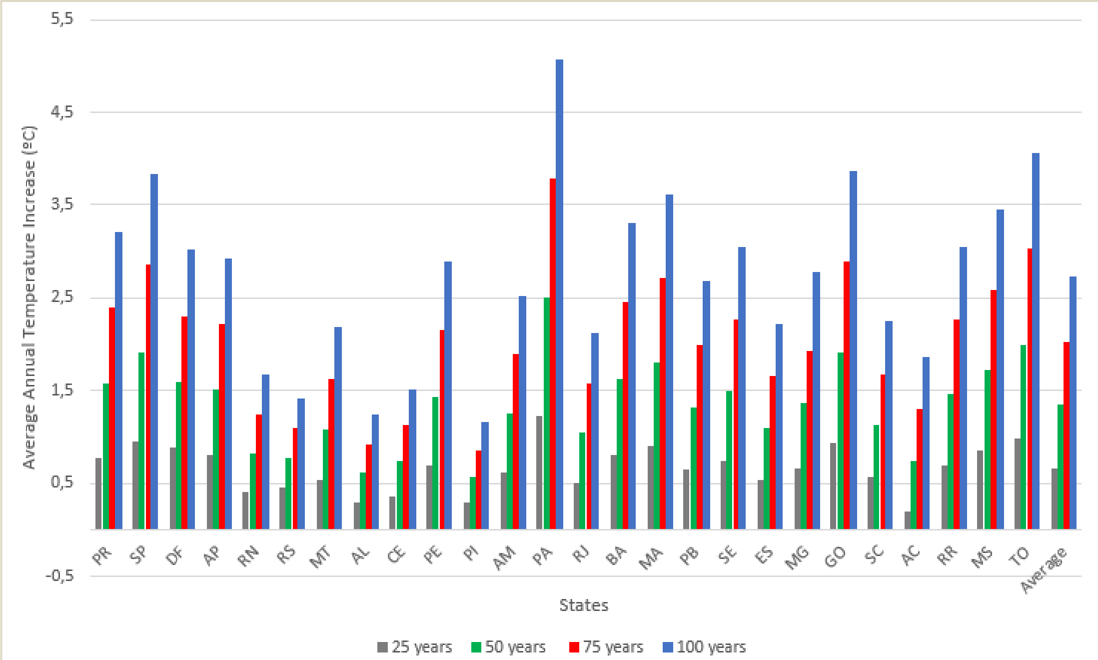

Figure 5 shows the calculated losses for the year 2020 in relation to the average annual temperature of each location, considering a constant irradiance of 1000 W/m². With this it is verified that in all the places there are already losses due to the temperatures and no system will generate according to its nominal power. It is concluded that this is a factor that always leads to the need to design systems with a higher power than the presently needed in order to compensate these and other losses. In the states further south of the country, where average annual temperatures are lower, annual losses will be lower, as temperatures are closer to 25 ºC.

The irradiance in the STC is considered to be 1,000 W/m², however, this value is only found at noon, for cloudless days (PEREIRA et al. 2017). With these data, it appears that the average is well below 1000 W/m², leaving Brazil with an average of 678.7 W/m² and an average insolation of 6.53 hours. This is the amount of solar energy reaching a surface perpendicular to the sun's rays per unit time per unit area. With thus reduced values of irradiance compared to the parameters STC (1000 W/m²), photovoltaic systems will also generate less electricity.

In Table 6, one can observe temperature differences in relation to 25 ºC and thus be able to better analyze the losses and gains of photovoltaic systems based on the STC. The temperature differences shown in this Table 6 in relation to 25 ºC will reach up to 8.42 ºC. This proves that these differences are increasing and, for the near future, perhaps the reference value will have to change to fit the current climate conditions. Consequently, the nominal powers of PV generation will be reduced if technologies more adapted to these global temperature levels are not found.

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Table 6: Differences in average annual temperatures in reference to 25 ºC

City	State	2020	2045	2070	2095	2120
Rio Branco	AC	1,06	1,20	1,81	2,37	2,92
Caracaraí	RR	2,75	3,45	4,23	5,02	5,80
Macapá	AP	2,75	3,56	4,27	4,97	5,68
Brasília	DF	-3,48	-2,59	-1,88	-1,17	-0,46
Paranaíba	MS	0,07	0,93	1,79	2,65	3,51
Chapeco	SC	-5,38	-4,82	-4,26	-3,70	-3,14
Própria	SE	1,66	2,39	3,16	3,93	4,70
Água Branca	AL	-1,66	-1,36	-1,05	-0,73	-0,43
Manaus	AM	2,72	3,34	3,97	4,61	5,25
Barreiras	BA	0,64	1,44	2,28	3,11	3,94
Fortaleza	CE	2,34	2,70	3,08	3,46	3,84
Vitoria	ES	0,10	0,88	1,44	1,99	2,55
Catalão	GO	-1,25	-0,26	0,71	1,69	2,66
São Luís	MA	2,58	3,49	4,39	5,29	6,20
Belo Horizonte	MG	-2,57	-1,90	-1,20	-0,64	0,20
Cuiabá	MT	1,88	2,40	2,96	3,51	4,06
Itaituba	PA	3,31	4,59	5,87	7,15	8,42
Monteiro	PB	-0,09	0,59	1,26	1,94	2,61
Cabrobó	PE	2,55	3,25	3,98	4,71	5,43
Teresina	PI	2,58	2,87	3,15	3,44	3,73
Londrina	PR	-2,73	-1,96	-1,15	-0,34	0,46
Campus	RJ	-0,21	0,30	0,83	1,36	1,89
Apodi	RN	3,03	3,43	3,85	4,27	4,69
Santa Maria	RS	-5,59	-5,14	-4,82	-4,50	-4,18
São Paulo	SP	-3,99	-3,04	-2,08	-1,13	-0,17
Porto Nacional	TO	3,07	4,00	5,02	6,04	7,07

Figure 6 shows a projection of increases in losses by mean annual temperature for up to 100 years. These losses in relation to the 25 ºC of the STC parameters were only considered annual mean temperatures. That is, the maximum temperatures on some days of the year will be much higher, and the operating temperatures of the solar panels can exceed 60 ºC. This means that temperature-related losses can exceed 15%.

Figure 5: Losses in maximum power in photovoltaic panels due to the average annual temperature of 2020.

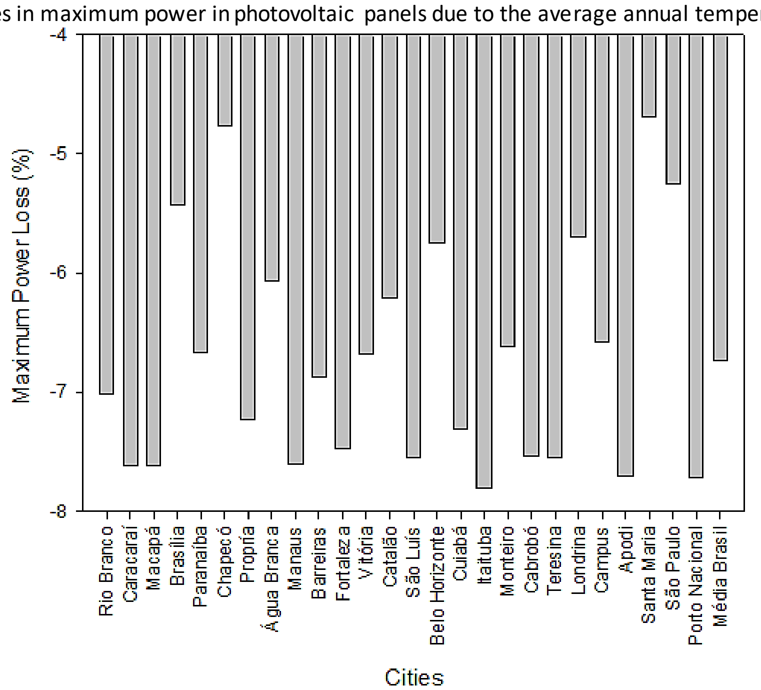

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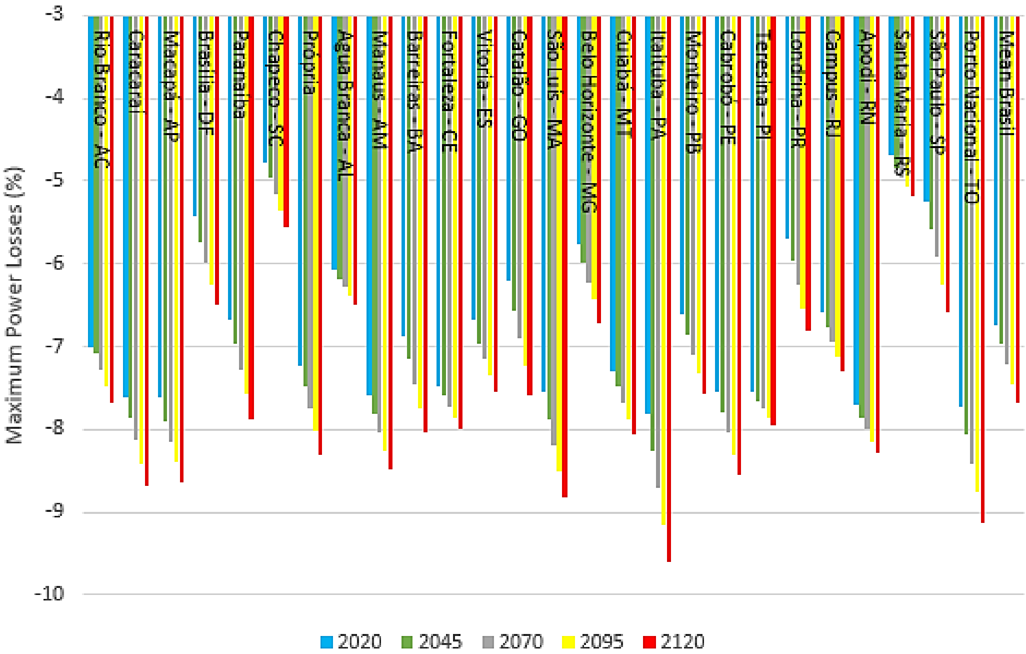
Figure 6: Projection of maximum power losses due to increased temperatures for photovoltaic generation.



4 CONCLUSIONS

This article analyzes existing residential photovoltaic systems in Brazil, taking into account the impacts of average ambient temperatures on their efficiency. Future climate projections are presented with their respective impacts on electricity generation. The impacts of changes in average annual temperatures on the generation potential of residential photovoltaic systems in Brazil caused by climate change were taken into account. It was verified that the PV sources, which already suffered great losses of efficiency in relation to the temperatures, they will gradually increase even more. Not all these climate changes discussed in this article cause major impacts on photovoltaic systems and these can be used without fear, even 100 years from now.

This article shows that each state in Brazil will be impacted in a different way, which results in a greater or lesser efficiency of the respective photovoltaic generation. As only average temperatures were analyzed here, future work could include an analysis of maximum temperatures, which would entail much more significant losses. Perhaps, some places in the country are already subject to higher temperatures and the modules can reach temperatures above the limit stipulated by the manufacturers and thus damage them.

The effect of environmental conditions on the temperature of photovoltaic cells, and therefore on their performance, has been explicitly accounted for here. Other factors that can affect the performance of photovoltaic modules are the distribution of the solar spectrum and the effect of air mass. Such factors were not taken into account in this article, but which may also impact future projections of photovoltaic generation.

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