Revista Brasileira de Geografia Física v.10, n.06 (2017) 1959-1973.

Revista Brasileira de Geografia Física

ISSN:1984-2295

Homepage: www.ufpe.br/rbgfe

Influence of Time Changes and Climate Variability on Photovoltaic Energy Production in the State of Maranhão

Francisco Emenson Carpegiane Silva Feitosa[1], Ramisa Cristina Rodrigues Belo[2], Jessflan Rafael Nascimento Santos[3], Mayara Lucyanne Santos de Araújo[4], Juliana Sales dos Santos[5], Fabrício Brito Silva[6]

[1] Bachelor of Environmental Engineering. MSc student in Climate Science – Universidade Federal do Rio Grande do Norte –*Campus* Natal. E-mail for correspondence: emenson.eng@gmail.com; [2] Bachelor student in production engineering – Universidade Ceuma – Campus Renascença. E-mail for correspondence: ramisa.rodrigues@hotmail.com ;[3] Bachelor of Environmental Engineering. MSc student in Environment – Universidade Ceuma – *Campus* Renascença. E-mail for correspondence: jessflan@ymail.com ;[4] Bachelor of Environmental Engineering. MSc student in Applied Geosciences – Universidade de Brasília. E-mail for correspondence: mayara.araujo.eng@gmail.com ;[5] Bachelor student in environmental engineering – Universidade Ceuma – *Campus* Renascença. E-mail for correspondence: julianasales.engenharia@gmail.com;[6] Bachelor in agronomy. MSc in agronomy. Doctor in Remote Sensing – INPE. Coordinator of the Masters in Environment at Ceuma University. E-mail for correspondence: fabricioagro@gmail.com

Artigo recebido em 12/05/2017 e aceito em 25/02/2018

R E S U M O

O objetivo deste estudo foi desenvolver uma metodologia para utilização de dados provenientes de sensoriamento remoto para o planejamento de projetos de energia fotovoltaica no Maranhão. Foram utilizados dados de radiação obtidos na base global GLDAS e precipitação proveniente do satélite TRMM, no período de 2001 a 2014. Os dados de radiação foram processados através da técnica de análise de séries temporais (ACP). O potencial de produção de energia fotovoltaica foi simulado considerando um sistema de 20 módulos fotovoltaicos, cada um com potencial nominal de 45Wp. Uma análise de regressão linear foi realizada para avaliar a correlação entre radiação e precipitação. Por último, o teste de Mann Kendall foi executado para avaliar as tendências nos dados de radiação e precipitação. Através da ACP foram identificadas duas Zonas homogêneas em relação à radiação, uma menor na região do Oeste (bioma amazônico) e a maior na região Leste do Estado (bioma cerrado). A precipitação respondeu por 21,3% na variação anual da radiação na região da Amazônia e 31,2% no Cerrado. A região de cerrado apresentou os maiores valores de radiação solar, e os menores valores foram registrados na região da Amazônia. Pelo teste de Mann Kendall, houve uma tendência linear de aumento na média mensal de radiação solar incidente na região amazônica e cerrado, tanto no período seco quanto no chuvoso. As análises mostraram um cenário favorável para produção de energia solar no Estado do Maranhão, com reduzido risco climático devido à tendência no aumento da radiação.
Palavras-chave: energias renováveis, planejamento energético, mudanças climáticas.

Climate Risk for Photovoltaic Energy Production in the state of Maranhão

ABSTRACT

The objective of this study was to develop a methodology for use of data from remote sensing in planning photovoltaic energy projects in Maranhao. Solar radiation data was obtained from global basis GLDAS and rainfall from the TRMM satellite, from 2001 to 2014. The radiation data were processed through the time series analysis technique (PCA). The photovoltaic power generation potential was simulated considering 20 photovoltaic module systems, each one with a nominal power of 45Wp. A regression analysis was performed to evaluate the correlation between radiation and precipitation. Finally, Mann Kendall's test was performed to evaluate trends in radiation and precipitation data. By PCA, two homogeneous zones were identified in relation to radiation, lower in the west (Amazon biome) and the largest east region of the state (Savanna biome). Rainfall represented 21.3% in the annual variation of radiation in the Amazon region and 31.2% in the Savanna. The Savanna region showed the highest solar radiation values and the lowest values were recorded in the Amazon region. By Mann Kendall's test, there was a positive linear trend of increase in the monthly average incident solar radiation in the Amazon region (Kendall's tau = 0.2173, $p < 0.0001$) and in the Savanna region (Kendall's tau = 0.1651, $p = 0.0011$). Analyses showed a favorable scenario for the production of solar energy in the state of Maranhao, with a low climate risk due to the trend in increased radiation.
Keywords: Renewable Energy, Energy Planning, Climate Change.

Introduction

In the last decade, photovoltaic solar energy (PV), technology used to convert solar radiation into electricity, has become a viable technology and has gained worldwide popularity. International competition, coupled with years of advanced manufacturing, research and development, has resulted in improved photovoltaic module efficiency, cost reduction and increased productivity (Gong, 2005). In particular, solar energy is seen as the most promising source of renewable energy because of the benefits it offers (Weinrub, 2011) and the production of energy from the sun has been on a gradual increase since 1850 (Foukal, 1990; Francis and Hengeveld, 1998).

In 2014, due to an increase of 7,171 MW, Brazil's installed electricity generation capacity reached 133,914 MW, with wind and solar parks accounting for 37.6% of this increase (Epe, 2015). The installed capacity of electricity from the sun will be about 4% of Brazil's total production in 2024. Currently, PV represents 0.02% of the country's electricity (Mme, 2015).

According to the National Energy Balance of 2016, in relation to the generation of electricity in Maranhão, 19.59% of the electricity produced comes from hydroelectric plants, 80.40% is from thermoelectric plants and 0.01% is represented by solar energy, sugar cane bagasse and diesel oil. In relation to the energy generated by fossil sources, the state highlights the production of natural gas (EPE, 2016).

Global solar radiation is determined by astronomical factors (e.g solar declination, day length), by atmospheric properties (including cloudiness, water vapor and aerosol) and to a lesser extent by surface conditions (land use, shading, albedo and orography). The radiative solar flux that reaches the surface of the Earth is influenced mainly by the space-time variability of the clouds (Dubayah and Loechel, 1997). Hence, cloudiness is the most active component of the solar radiation flux of the Earth-Atmosphere system (Salby, 1996), reflecting about 30% of incident solar radiation into space, thereby reducing the surface energy balance.

Nature and human activities release greenhouse gases into the atmosphere that change their composition, disrupting the balance between incoming and outgoing radiant energy, thus producing important effects on climate dynamics (IPCC, 2014). Photovoltaic energy contributes significantly to reducing the emission of these gases (Alsema, 2000). In Brazil, it is estimated that every 1KWp of photovoltaic energy generated, and connected in the distribution network, will be reduced by 1,359 kg of CO_2 (Krauter and Ruther, 2003).

Remote sensing and geoprocessing (GIS) can be used to assess the potential of several renewable energy alternatives, including aspects such as geographic location (Wang and Koch, 2010), technology used for renewable energy, economic viability (De Vries et al., 2007), among others. The importance of GIS in this type of evaluation has been highlighted. Several studies focused on solar energy (Trieb, 2009) to determine the potential for photovoltaic power generation and identify the ideal locations for technology implementation and thus improve project efficiency (Wang and Koch, 2010). One of the main contributions of geotechnologies is due to the fact that it compensates for the lack of surface measurement instruments in remote places such as the Amazon. Compared with measurements of other meteorological variables, the measurement of solar radiation presents the highest degree of uncertainty (Moradi, 2009).

In conclusion, precipitation represents a negative component in the radiation balance incident on the planet (Harison et al., 1990). Therefore, the focus of the present study was to estimate the values of incident solar radiation and to verify how much the precipitation values interfere with incident solar radiation in the state of Maranhão, in order to generate subsidies for the growth of photovoltaic energy production in the state.

Materials and Methods

Study Area

The State of Maranhão is located in the extreme western part of the Brazilian Northeast and extreme east of the Amazon Basin (Figure 1). The State is home to a transitional area between the Cerrado and Amazon biomes, which implies an area of high climatic variability as well as a great biodiversity recognized internationally (Serafini, 2007).

Regarding climate diversity, the state presents warm and humid tropical climate to the northwest, typical of the Amazon region. In the Southeast, it is marked by warm and semi-humid tropical climate. The vegetation reflects the transitional aspects of the climate and soil conditions of the transition region between the Amazon (wet) and northeast (semi-arid) regions, from which varied ecosystems have emerged, ranging from coastal environments with mangrove swamps, through flooded, to the dense ombrophilous forest, characteristic of the Amazon (Muniz, 2006).

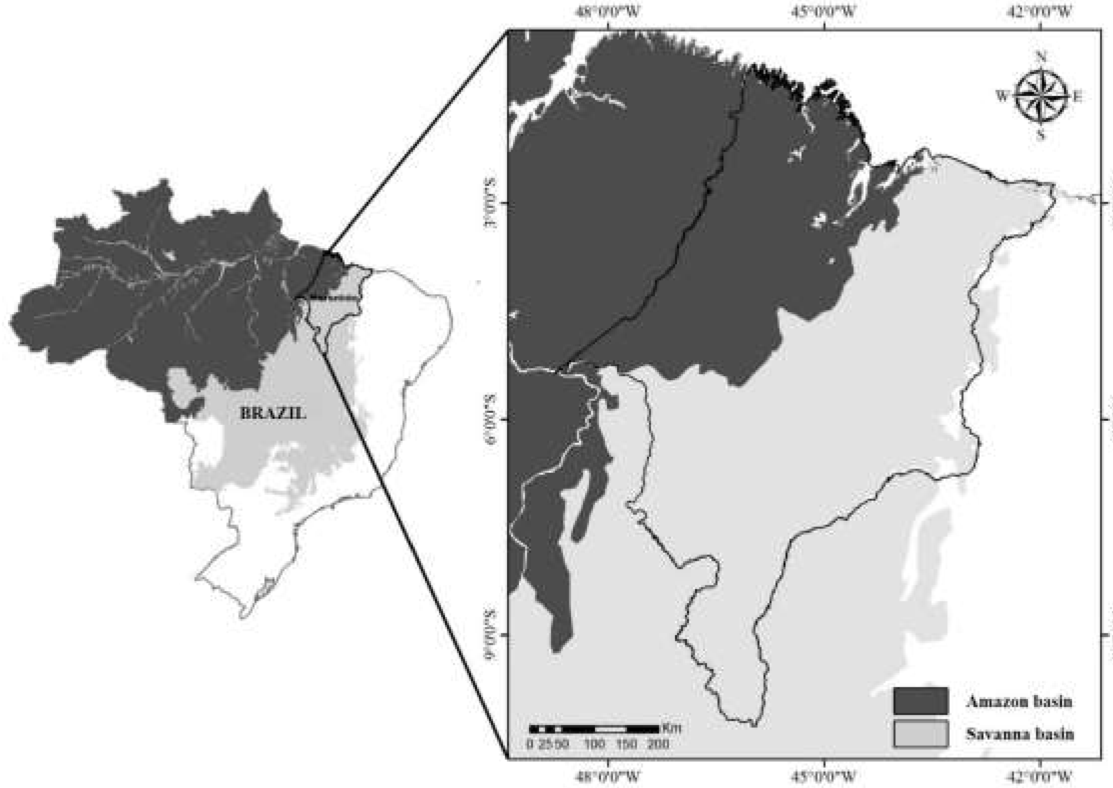


Figure 1. Study area highlighting the location of the state of Maranhão in a transition area between the Amazon and Cerrado biomes.

Methodological Procedure

Data from surface incident and precipitation radiation were obtained from the Global Land Data Assimilation System (GLDAS) and Tropical Rainfall Measuring Mission (TRMM), respectively. The two bases compose a time series of 14 years (2001 and 2014), present monthly temporal resolution and spatial resolution of 0.25°. The solar radiation data showed a unit of $Wh.m^{-2}.d^{-1}$ and the monthly averages of precipitation is presented with the unit mm.

In order to reduce the dimensionality of the data and represent the maximum spatial variability, Principal Component Analysis (PCA) was performed. The first image of the PCA, because it presented the maximum spatial variability, was used to perform a cluster analysis technique called k-means, with the objective of generating a classified image in which it presents the classes (Homogeneous zones) referring to the radiation incident on the surface (Mather and Koch, 2010).

From the classes identified in the cluster analysis, the monthly mean values of surface incident radiation and precipitation were calculated, thus generating the time series of each class.

Linear regression analysis was used to characterize the relationships between incident solar radiation and precipitation. For the verification of trends of increase or decrease in the time series, the Mann-Kendall test was used, with a confidence level of 10% (Kendall, 1955).

Simulation of photovoltaic power generation

In the design of a photovoltaic system, the required or desired nominal power condition must be considered. Another important factor is the calculation of the number of photovoltaic modules N needed to meet the nominal power of the generator calculated previously or stipulated. The calculation takes into account the total nominal power of the photovoltaic plant Pt in Wp (Watt peak), and the nominal power of each panel Pp, also in Wp (Eq.1).

$$N = Pt / Pp \quad (1)$$

The total number of hours of full sun (H), that is the number of hours that the solar radiation should remain constant at 1000 Wm^{-2} of irradiated solar energy (Eq. 2) (Alves and Souza, 2014).

$$H = Rt / 1000 \quad (2)$$

Where Rt is the incident daily solar radiation ($kWh.m^{-2}$).

The energy produced by the array of photovoltaic modules is calculated using the following equation:

$$Ep = Pt.\ H.\ \eta T \qquad (3)$$

Where Ep represents the energy produced (in kW), ηT is the efficiency factor of the converter. It was considered that the inverter has an efficiency factor of 93%. In this work, the photovoltaic module with a nominal power of 45Wp KC-50T model produced by Kyocera manufacturer was used as an example, resulting in the need to use an array of 20 modules with a total nominal power of 900 Wp.

In this study, the prices of components and materials were not included, because economic viability is not the objective of this article.

Results and discussion

Solar Radiation Zoning

The methodology for processing the incident radiation data on the surface generated a map consisting of two Zones (classes) (Fig. 1). Through a visual analysis, it was possible to perceive a spatial correspondence between the Zones identified and the regions of the biomes Amazon (west) and Cerrado (east).

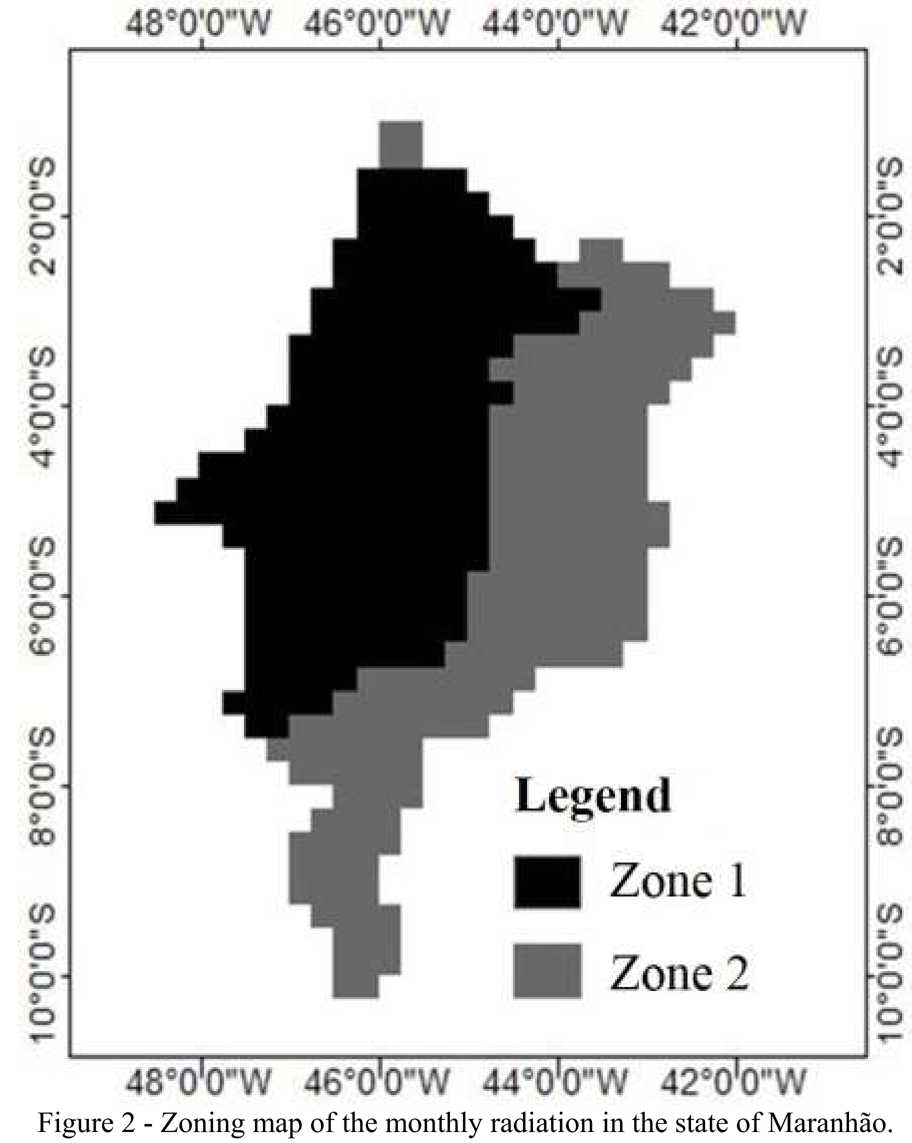


Figure 2 - Zoning map of the monthly radiation in the state of Maranhão.

The time series of precipitation and incident solar radiation were calculated considering the zones identified.

Table 1 presents the precipitation values along the time series studied (2001 to 2014) in Zone 1. Considering the rainy season the period of months with monthly precipitation above 100 mm was possible to observe the beginning of the rainy season between November and January , and, beginning of the dry season between May and July. Considering the annual total, in 2012 (1306.6 mm) the lowest values were observed and the largest occurred in 2011 (2095.6 mm).

Table 1: Monthly variation of precipitation (mm) in Zone 1 between 2001 and 2014.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Total
2001	227,8	295,2	351,3	400,6	121,7	121,9	56,0	7,7	16,7	25,7	78,2	89,8	**1792,5**
2002	410,4	154,8	268,2	334,1	190,9	92,4	36,6	8,7	24,7	19,8	51,6	110,5	**1702,7**
2003	196,3	372,2	356,1	281,7	170,7	99,8	33,4	33,7	15,3	15,3	85,7	85,5	**1745,7**
2004	395,2	401,8	360,4	256,2	122,1	78,4	68,6	41,9	19,9	35,2	42,6	82,1	**1904,2**
2005	168,6	243,3	380,5	232,7	167,3	93,5	38,8	13,4	9,4	18,1	70,8	176,8	**1613.1**
2006	137,4	266,2	368,3	440,2	237,0	61,5	30,4	36,0	22,9	41,9	111,0	73,8	**1826.6**
2007	77,0	450,2	274,1	301,2	135,3	55,2	40,7	16,4	14,9	40,5	43,3	121,0	**1569.9**
2008	254,8	255,5	491,6	300,8	229,5	93,7	47,7	27,9	9,1	34,7	57,5	143,1	**1946.0**
2009	137,7	329,2	347,7	472,7	392,5	90,1	47,5	23,8	8,5	46,7	19,1	120,2	**2035,7**
2010	205,1	172,2	160,7	299,9	136,6	90,6	69,8	16,6	6,2	69,6	67,0	146,5	**1440,7**
2011	321,2	413,2	314,0	346,5	230,3	77,7	85,0	33,8	6,6	95,1	126,6	45,6	**2095,6**
2012	169,7	248,4	282,1	161,4	72,2	77,0	37,3	19,8	16,7	32,6	73,4	116,0	**1306,6**
2013	168,7	196,6	275,7	203,8	174,7	70,2	70,4	17,8	19,6	43,0	111,7	98,3	**1450,3**
2014	223,5	328,0	263,8	288,5	243,8	74,3	26,6	14,4	26,0	37,1	63,7	99,0	**1688,6**
Monthly average	**200,7**	**280,7**	**330,8**	**300,3**	**172,7**	**84,2**	**44,1**	**18,8**	**16,0**	**36,1**	**68,9**	**104,8**	**1722,7**

Table 2 presents the precipitation values along the time series studied (2001 to 2014) in Zone 2. Considering the rainy season as the period with monthly precipitation above 100 mm it was possible to observe the beginning of the rainy season between October and January, and, beginning of the dry season between May and June. Considering the annual total, in 2012 (1102.0 mm), the lowest values were observed and the highest values occurred in 2009 (1968.3 mm).

Table 2: Monthly variation of precipitation (mm) in Zone 2 between 2001 and 2014.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Total
2001	166,0	253,3	283,7	294,0	91,2	75,7	21,4	2,7	18,6	38,0	103,5	126,7	**1474,9**
2002	396,1	139,1	231,7	212,3	117,9	55,3	21,7	3,3	42,2	32,5	62,3	137,6	**1451,8**
2003	197,4	327,2	268,1	187,7	131,8	65,3	9,5	22,5	13,0	23,0	92,2	98,6	**1436,4**
2004	411,7	356,2	285,7	237,4	81,2	47,3	30,7	24,6	14,2	41,0	61,9	93,5	**1685,3**
2005	172,1	238,7	347,2	149,5	110,0	47,7	29,1	3,1	11,2	21,0	70,4	181,1	**1381,0**
2006	109,4	256,0	316,9	392,6	186,1	35,5	8,4	22,3	32,9	68,3	99,0	97,5	**1625,2**
2007	72,8	424,7	187,5	227,6	90,8	20,5	23,6	4,3	9,9	31,4	59,0	90,1	**1242,2**
2008	275,6	217,5	401,3	313,8	172,5	58,3	25,3	12,5	13,3	24,0	80,0	139,2	**1733,5**
2009	171,5	273,6	266,9	486,8	358,9	50,6	28,3	13,8	14,0	82,5	42,4	179,1	**1968,3**
2010	181,9	170,9	168,4	234,4	84,0	82,1	30,6	4,0	8,4	77,3	74,0	148,7	**1264,7**
2011	237,5	352,2	258,8	313,6	180,4	32,2	45,1	18,0	5,1	115,4	160,6	72,6	**1791,5**
2012	189,1	219,0	233,4	105,6	39,8	40,4	13,6	6,0	7,9	34,9	104,4	108,0	**1102,0**
2013	230,1	179,0	249,3	181,4	104,4	54,4	39,7	5,1	14,4	65,5	156,0	130,6	**1410,0**
2014	192,9	249,9	208,1	218,1	216,2	38,3	8,5	7,9	20,1	50,0	109,9	121,5	**1441,3**
Monthly average	**214,6**	**261,2**	**264,8**	**253,9**	**140,4**	**50,3**	**24,0**	**10,7**	**16,1**	**50,4**	**91,1**	**123,2**	1500,6

Table 3 shows the values of monthly incident solar radiation in Zone 1 and it was possible to observe the minimum value around 5000 $Wh.m^{-2}.d^{-1}$ in January, February and April. The maximum monthly average solar radiation in Zone 1 was observed in August and September (dry period) with 6137 and 6204 $Wh.m^{-2}.d^{-1}$, respectively. Considering the annual total, in Zone 1 the highest values of total annual solar radiation occurred in 2001 (70406 $Wh.m^{-2}.d^{-1}$). The lowest values were observed in 2003 (58018 $Wh.m^{-2}.d^{-1}$).

Table 3: Monthly variation of daily solar radiation (Wh. $M^{-2}.d^{-1}$) in Zone 1 between 2001 and 2014.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Mean
2001	3670	3664	5756	5606	5800	6065	6348	6929	7096	6848	6282	6343	**70406**
2002	6020	6636	6430	6007	6050	6020	5681	5877	5377	4798	4728	4393	**68018**
2003	4408	4352	4172	4387	4804	4971	5786	5475	5434	4928	4771	4533	**58018**
2004	4540	4240	4249	4572	4972	5298	5406	5411	5064	4870	5020	4653	**58295**
2005	5134	4883	4646	4917	4959	5178	5955	6110	5902	5024	4638	4604	**61950**
2006	4727	5095	4629	4118	4541	5437	5369	5931	5709	4837	4917	4878	**60188**
2007	4935	4310	4901	4797	4889	5584	5162	6465	6801	5694	5212	5152	**63902**
2008	4990	5499	4897	5023	5412	5643	5671	6312	6634	6619	5580	5208	**67490**
2009	5681	5607	5632	5119	4958	5666	5832	6104	5851	5300	5326	4865	**65942**
2010	5331	4869	5138	4622	5177	5666	5884	6343	6845	5579	5125	5204	**65783**
2011	5001	4948	5358	5275	5179	5919	6132	5511	6792	5294	5287	5656	**66352**
2012	5124	5276	5811	5594	5475	5217	5725	6501	6622	5694	5178	5588	**67805**
2013	5298	5711	5611	5923	5396	5653	5899	6511	6379	5674	4931	5313	**68297**
2014	5072	4823	5165	5238	4819	5561	5809	6441	6354	5892	5691	5360	**66225**
Monthly mean	**4995**	**4994**	**5171**	**5086**	**5174**	**5563**	**5761**	**6137**	**6204**	**5504**	**5192**	**5125**	**64905**

Table 4 shows the values of monthly incident solar radiation in Zone 2 and it was possible to observe the minimum value of 5173 $Wh.m^{-2}.d^{-1}$ in February. The maximum value of 6724 $Wh.m^{-2}.d^{-1}$ was observed in September.

Considering the total annual incident solar radiation, in 2001 the highest value was recorded, as 72170 $Wh.m^{-2}.d^{-1}$ while the lowest value was recorded in 2003 (62310 $Wh.m^{-2}.d^{-1}$).

Table 4: Monthly variation of daily solar radiation (Wh. $M^{-2}.d^{-1}$) in Zone 2 between 2001 and 2014.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual mean
2001	3967	3975	5814	5785	5905	6126	6387	6960	7320	6982	6367	6581	**72170**
2002	6249	6819	6486	6074	6075	6005	5880	6260	5957	5531	5289	4696	**71322**
2003	4732	4544	4389	4621	4916	5192	6165	5697	6116	5834	5256	4848	**62310**
2004	4412	4535	4560	4728	5415	5496	5742	6161	6190	5511	5613	5122	**63486**
2005	5264	5088	4693	5145	5104	5353	6251	6592	6660	5868	5175	4924	**66117**
2006	5211	5142	4798	4234	4800	5598	5643	6517	6298	5207	5346	5156	**63949**
2007	5025	4445	5242	4820	5268	5682	5230	6832	7208	6430	5688	5466	**67336**
2008	5001	5528	5036	5261	5629	5768	5697	6489	7110	6955	5946	5329	**69750**
2009	5824	5782	5979	5252	5057	5854	5957	6297	6275	5146	5995	5312	**68730**
2010	5630	5182	5229	5143	5487	5868	6233	6556	7218	5978	5533	5262	**69318**
2011	5196	5019	5513	5434	5440	6055	6240	5509	7069	5664	5399	5963	**68501**
2012	5265	5471	5847	5890	5649	5369	5929	6648	7094	6496	5260	5844	**70762**
2013	5351	5941	5651	5910	5506	5706	5980	6761	6773	6035	5140	5481	**70234**
2014	5327	4950	5127	5353	5080	5753	5999	6772	6847	6183	5964	5562	**68916**
Monthly mean	**5175**	**5173**	**5312**	**5261**	**5381**	**5702**	**5952**	**6432**	**6724**	**5987**	**5569**	**5396**	68064

Figure 3 presents the monthly mean values of incident solar radiation ($Wh.m^{-2}.dia^{-1}$) and precipitation (mm) estimated throughout the year. The highest values of precipitation occur between January and April (rainy season), during these months the lowest values of solar radiation were observed. After this period, an increase in radiation values was observed. In August and September, the maximum values of solar radiation are verified, consequently, in these months the minimum values of precipitation occur (dry period).

In Zone 2, the highest amounts of solar radiation and the lowest values of precipitation were observed throughout the year, compared to Zone 1, because in the Amazonian biome less atmospheric pressure occurs (Molion, 1987), therefore this region tends to have larger incidence of precipitation.

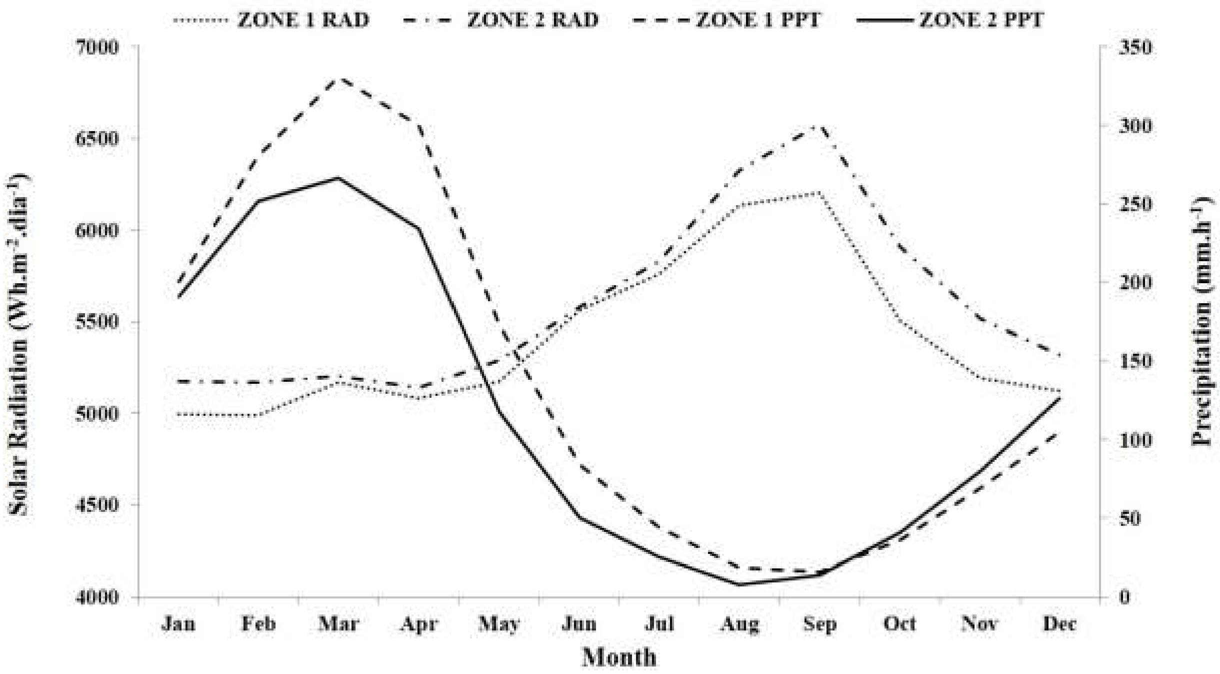


Figure 3 - Variation of monthly averages of incident radiation and precipitation.

.

For the months of February and March, there was a gradual increase in the radiation incident on the surface of the Erath measured in one month in relation to the other, with a significant decrease in April. These differences are related to changes in the declination of the Sun throughout the year, which is associated with a set of astronomical factors such as the translation movement and the inclination of the Earth's axis (Varejão-Silva, 2006).

The large increase in radiation values between the months of May and September, observed in both regions, is due to the transition between the rainy season and the dry season, which indicates the possibility of a sky with few clouds and elevated temperatures. As of October, these values decrease until reaching their minimum values in January and February.

Comparing the data of solar radiation and precipitation, it was possible to observe that the maximum values of incident solar radiation were observed in the dry season and the minimum values in the rainy season in the regions of the Amazon and Cerrado, where possibly the cloudiness may explain this variation (Dal Pai and Escobedo, 2014; Filho et al., 2006; Liepert, 2002; Stanhill and Cohen, 2005; Wild et al., 2005).

In this case, cloud cover is considered a significant factor in reducing the incidence of radiation (Rocha et al., 2004). However, the same fact was not observed when analyzing the total annual values of both variables, where the highest and lowest values were observed in different years.

Analysis of trends in solar radiation and precipitation data

Using the Mann Kendall method, solar radiation and precipitation data were analyzed annually and seasonally in Zones 1 and 2. For the precipitation trends tended to be negative, but with a small and non-significant linear trend ($p > 0.1$). Hastenrath & Greischar (1993) and Silva et al. (1998) also did not identify significant trends in precipitation in the northeastern region of Brazil for wet and dry seasons. However, precipitation in this region is very sensitive to the extreme values of the sea surface temperature in the Equatorial Pacific associated with ENSO, such as the anomalies in the surface temperature of the Atlantic Ocean related to the dipole temperature anomalies of the surface of the Atlantic Ocean (Costa et al., 2016).

Regarding the annual and seasonal solar radiation in relation to the months (Table 5), trends were positive (with a common direction) and significant ($p < 0.1$). For the analysis of annual solar radiation in Zone 1, the test showed a standard deviation of 29.9%, the minimum value was 135.0 $W.m^{-2}$ and the maximum was 295.7 $W.m^{-2}$. For Zone 2, there was a standard deviation of 30.6%, 146.0 $W.m^{-2}$ (the minimum value) and 305.0 $W.m^{-2}$ (the maximum value).

The trend analysis showed that solar radiation has been increasing over the last 14 years, in relation to the precipitation analysis and small decreasing trends were identified, but were not significant.

Table 5 - Linear trends and significance for each zone and period of incident solar radiation on the Earth's surface using the Mann Kendall test.

Zone	Duration		Anually		Rainy Season		Dry Season	
	Initial	End	Linear Trend	Kendall's tau	Linear Trend	Kendall's tau	Linear Trend	Kendall's tau
1	2001	2014	0,0057	0,2173	0,0058	0,3154	0,0046	0,1836
2	2001	2014	0,0051	0,1651	0,0046	0,2847	0,0046	0,2227

Simulation of photovoltaic energy production in Maranhão

From the arrangement of photovoltaic modules used to estimate the energy generated in each Zone (900 Wp), with respect to the annual analyzes (Fig. 2), it has been shown that for all years, total energy production was higher in the cerrado biome (Zone 2) than in the Amazon biome (Zone 1). In 2001, the highest potential electricity production, around 1.9 $MWh.year^{-1}$ in Zone 2 and 1.86 $MWh.year^{-1}$ in Zone 1, the lowest values were recorded in 2003; in Zone 1 it was observed at about 1.53 $MWh.year^{-1}$ and 1.64 $MWh.year^{-1}$ for Zone 2. By 2014, excellent values of electricity production could be observed, above 1.7 $MWh.year^{-1}$ for Zone 1 and Zone 2. The difference in electricity production from Zone 2 in relation to Zone 1 was 4%.

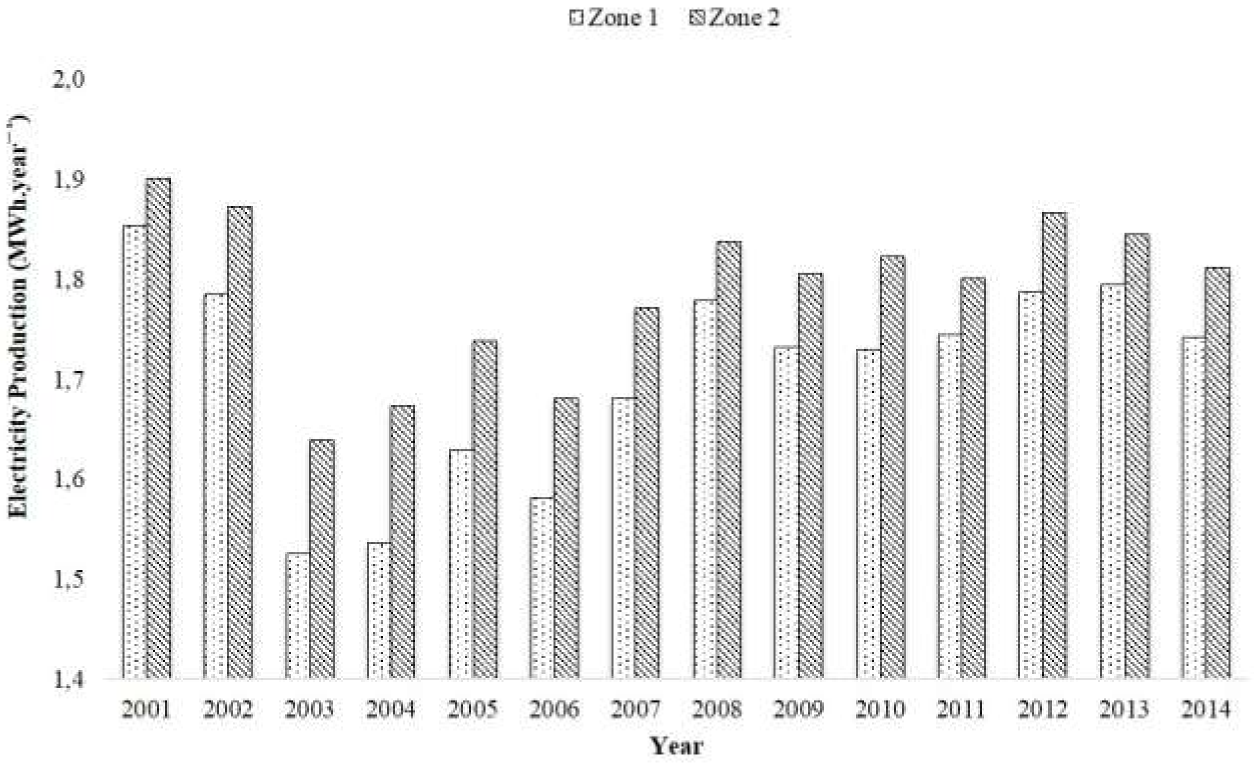


Figure 4: Simulation of electricity production from 2001 to 2014 in Zones 1 and 2.

In relation to the average monthly electricity production in 2014, the results showed that the electricity produced in each Zone could meet the average monthly consumption typical of a residence in the state of Maranhão throughout the year. Thus, the difference between the demand for electricity and energy generated is a total of 368 kWh in Zone 2 and 297 kWh corresponding to Zone 1 (Fig. 5).

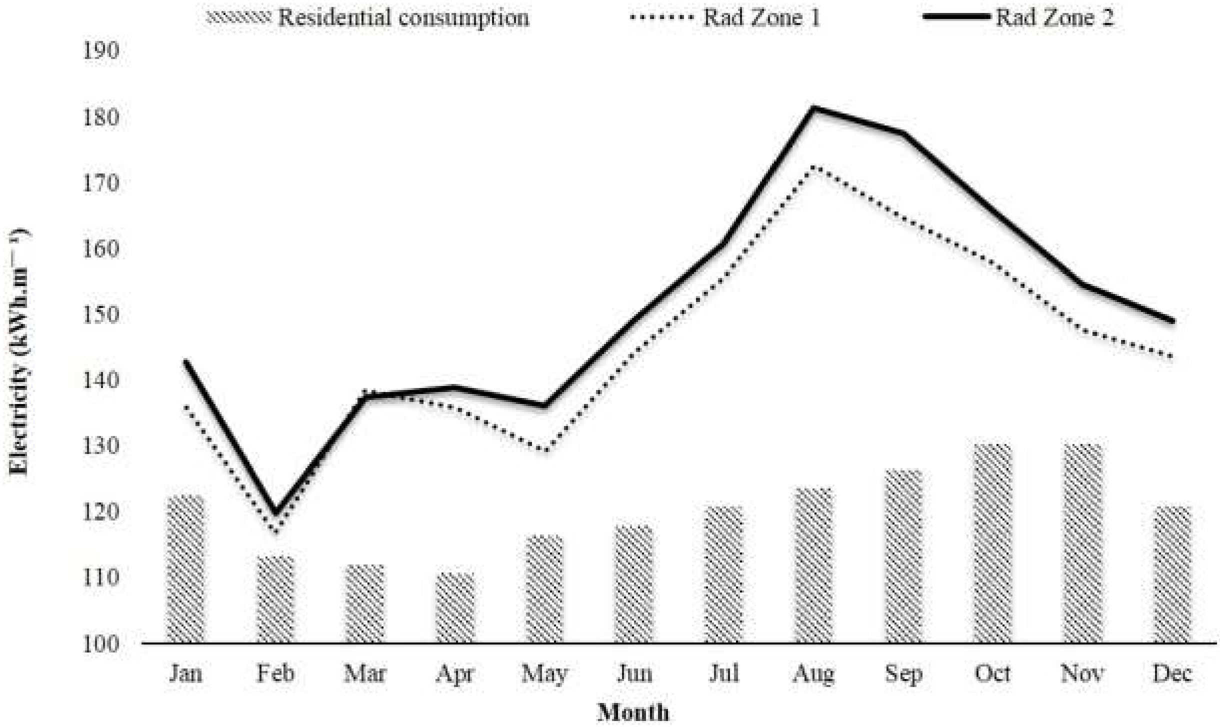
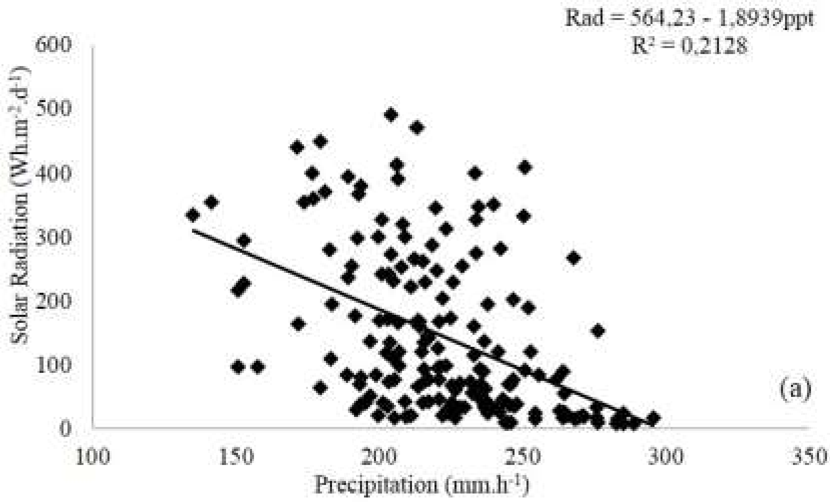
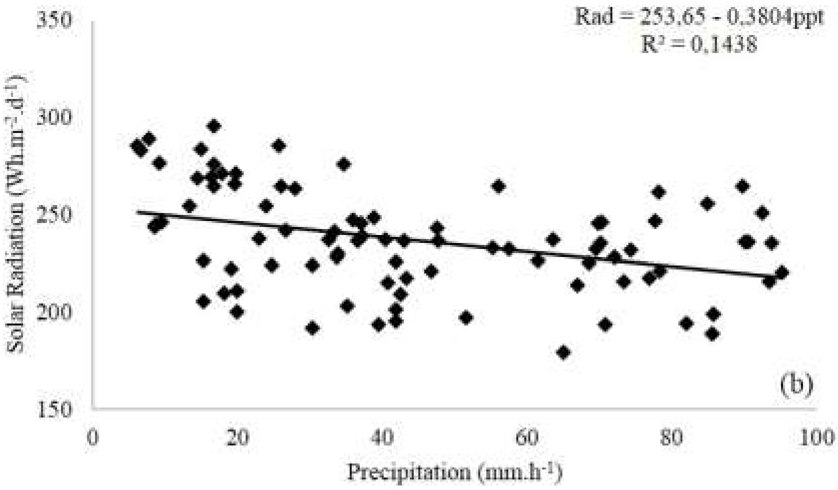


Figure 5 - Comparison between energy generated and average residential consumption in the state of Maranhão in the year 2014.

Correlation of Incident solar radiation x Precipitation

Considering the correlation between precipitation and incident solar radiation, the radiation values decreased with increasing precipitation values. According to the annual analysis, rainfall represented a 21.3% variation in the radiation data in Zone 1 (Amazon biome) (r^2 = 0.2128), 14.4% in the dry period (r2 = 0.1438) and in relation to the rainy season only 2.53% (r2 = 0.0253) correlation with solar radiation (Fig. 6). Regarding the annual series at each 10-mm increase in precipitation data / month, it corresponded to a decrease of 18.9 $W.m^{-2}$, producing 11.8 $kWh.m^{-1}$ less in power generation in the Amazon. In the dry season, if precipitation exceeds 10 mm per month, the amount of radiation will reduce by 3.80 Wm^{-2}, resulting in the production of 2.4 $kWh.m^{-1}$ less energy and 0.40 Wm^{-2} in the rainy season, estimated at 0.25 $kWh.m^{-1}$ less energy generated.





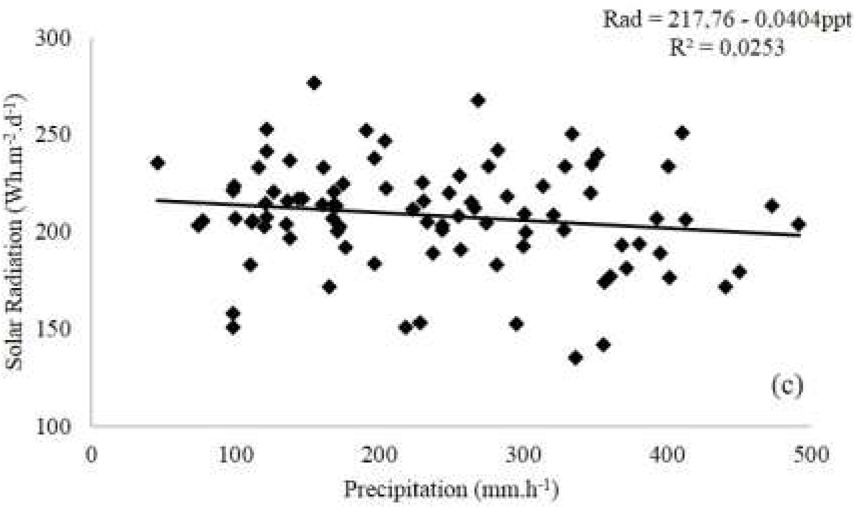


Figure 6 - Correlation of solar radiation with precipitation in Zone 1 (a) Annual, (b) Dry Period and (c) Rainy season.

In the Cerrado biome, in the annual period analyzed, the precipitation corresponded to 31.2% (r^2 = 0.3122) of the variation of the values of the incident radiation, 34.2% (r^2 = 0.3418) in the dry period and 10.2% in relation to the rainy season. Analyzing these correlations, a fall of 19.9 Wm^{-2} was observed in the cerrado region, with a 10-mm increase in precipitation / month, producing 12.4 $kWh.h^{-1}$ less in energy generation. In the dry season, a decrease of 6.29 Wm^{-2} was observed, generating 3.91 $kWh.h^{-1}$ less energy and in the rainy season a decrease of 0.92 Wm^{-2} was measured, producing 0.57 $kWh.h^{-1}$ less than the energy produced (Fig. 7).

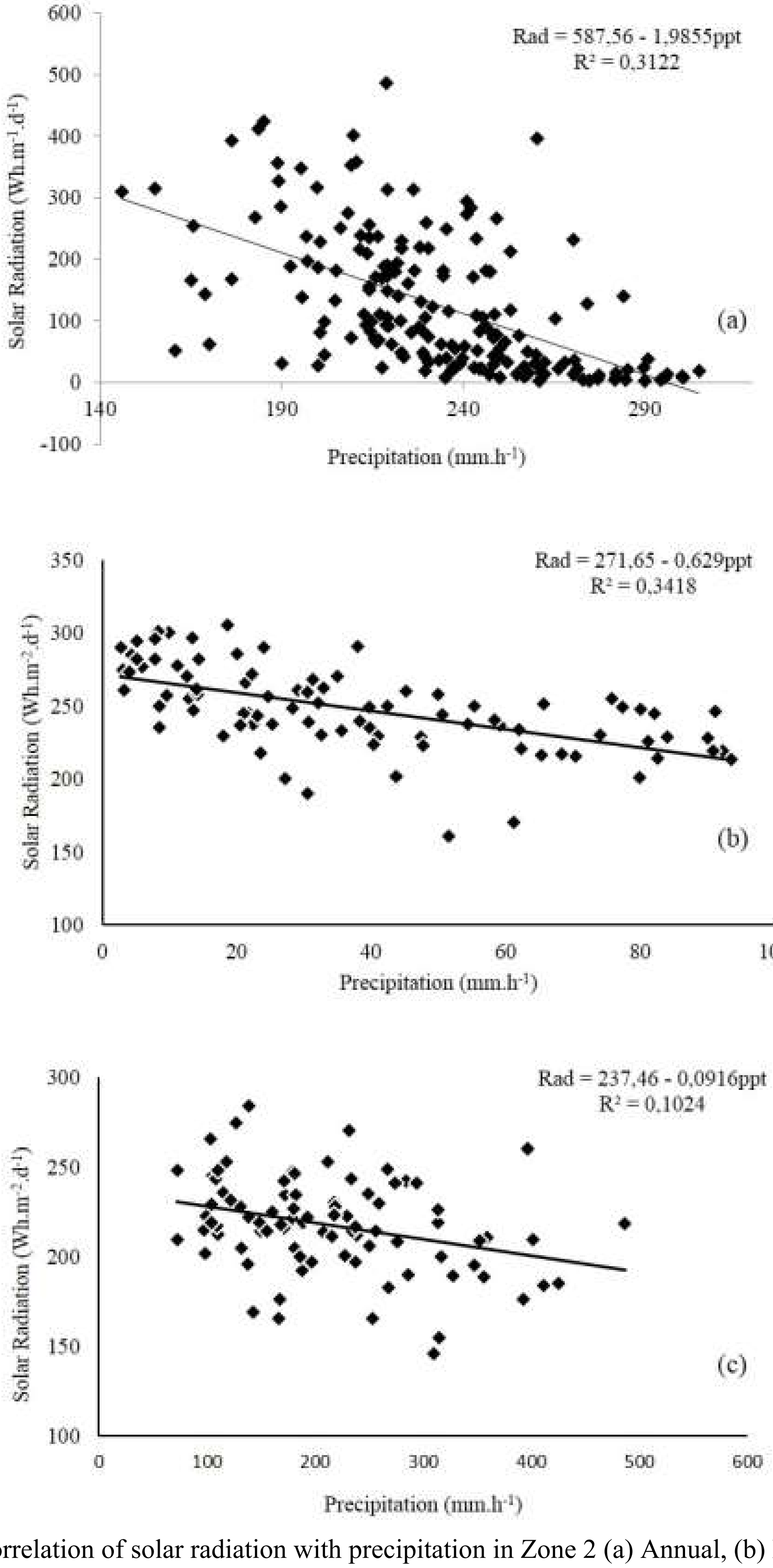


Figure 7 - Correlation of solar radiation with precipitation in Zone 2 (a) Annual, (b) Dry Period and (c) Rainy season.

Taking into account the residential demand for electricity, the results were insignificant, however, one must take into account the correlation if we analyze large-scale projects of photovoltaic energy production.

The relationship between radiation and precipitation was stronger in Zone 2, because the cerrado region has lower precipitation rates than the Amazon, however, other factors (cloud cover, water vapor, aerosols, etc.) may also explain this difference.

Conclusion

According to the results, there was a linear trend of increase in solar radiation data. Regarding the variation of the values of solar radiation throughout the year, it was inferred that the main causes are the increase of cloudiness and water vapor in the rainy season. The higher values of radiation observed in Zone 2 can generate subsidies in the formulation of plans for the installation of solar power plants in the region. However, this zone has a higher percentage of variation in relation to precipitation. In addition, more research is needed, as well as better experimental measures for the evaluation of surface-incident solar radiation and precipitation (as standard rain gauge), since these variables react differently to astronomical and climatic conditions.

Acknowledgement

The authors would like to thank Ceuma University (UNICEUMA) and the State of Maranhão Research Support Foundation (FAPEMA).

References

Alsema, E. A. Energy pay- back time and CO2 emissions of PV systems, 2000. Progress in photovoltaics: research and applications, v. 8, n. 1, p. 17-25.

Alves, R. D. S., Souza, A. S. D., 2014. Manual de engenharia para sistemas fotovoltaicos. Igarss 2014 530.

Costa, M. da S., Lima, C. L., Gonçalves, K. A., 2016. Tendências observadas em extremos de precipitação sobre a região Semiárida do Nordeste do Brasil (Trends observed in precipitation extremes over the semiarid region of Notheast Brazil). Revista Brasileira de Geografia Física, v. 8, n. 5, p. 1321-1334.

Dal Pai, Enzo; Escobedo, J. F., 2014. Estimativa da radiação atmosférica em função dos índices radiométricos kt e kd para botucatu-SP. Energia na Agricultura, v. 30, n. 2, p. 172-179.

De Vries, Bert JM; Van Vuuren, Detlef P.; HOOGWIJK, Monique M., 2007. Renewable energy sources: Their global potential for the first-half of the 21st century at a global level: An integrated approach. Energy policy, v. 35, n. 4, p. 2590-2610.

Dubayah, R., Loechel, S., 1997. Modeling Topographic Solar Radiation Using GOES Data. J. Appl. Meteorol. 36, 141–154.

Epe (Empresa de Pesquisa Energética), 2015. Balanço Energético Nacional, ano base 2014. Ministério de Minas de Energia, Brasília.

Epe, E. d. P. E., 2016. Balanço Energético Nacional 2016 - Ano base 2015, Brasília: Ministério de Minas e Energia.

Filho, J. D. C. S.; Ribeiro, A.; Costa, M. H.; Cohen, J. C. P.; Rocha, E. J. P., 2006. Variação sazonal do balanço de radiação em uma floresta tropical no nordeste da Amazônia. Revista Brasileira de Meteorologia, v.21, n.3b, 318-330.

Foukal, P., Lean, J., 1990. An Empirical Model of Total Solar Irradiance Variation Between 1874 and 1988. Science (80-.). 247, 556–558.

Francis, D., Hengeveld, H., 1998. Extreme Weather and Climate Change, Atmospheric Environment.

Gong, X., Kulkarni, M., 2005. Design optimization of a large-scale rooftop photovoltaic system. Sol. Energy 78, 362–374.

Harrison, E.F., Minnis, P., Barkstrom, B.R., Ramanathan, V., Cess, R.D., Gibson, G.G., 1990. Seasonal variation of cloud radiative forcing derived from the Earth Radiation Budget Experiment. J. Geophys. Res. Atmos. 95, 18687–18703.

Hastenrath, S., Greischar, L., 1993. Further work on the prediction of northeast Brazil rainfall anomalies. J. Clim.

IPCC Climate Change 2014: Synthesis Report (eds Pachauri, R. K. & Meyer, R. L.) (Cambridge Univ. Press, 2014).

Kendall, M. G. (1955), Rank Correlation Methods, 2nd ed., Charles Griffin, London.

Krauter, S.; Rüther, R., 2004. Considerations for the calculation of greenhouse gas reduction by photovoltaic solar energy. Renewable Energy, v. 29, n. 3, p. 345-355.

Liepert, B.G., 2002. Observed reductions of surface solar radiation at sites in the United States and worldwide from 1961 to 1990 29, 1–4.

Mather, Paul M.; Koch, Magaly. 2010. Preprocessing of Remotely- Sensed Data. Computer Processing of Remotely-Sensed Images: An Introduction, Fourth Edition, p. 87-124.

MME (Ministério de Minas e Energia), 2015. Plano Decenal de Energia Elétrica 2024. BRASIL/MME, Brasília.

Molion, L. C. B., 1987. Climatologia dinâmica da região amazônica: mecanismos de precipitação. Revista Brasileira de Meteorologia, v. 2, n. 1, p. 107-117.

Moradi, I., 2009. Quality control of global solar radiation using sunshine duration hours. Energy 34, 1–6.

Muniz, F. H., 2006. A vegetação da região de transição entre a Amazônia e o Nordeste: diversidade e estrutura. In: Emanoel Gomes de Moura. (Org.). Agroambientes de transição entre o Trópico Úmido e o Semi-árido do Brasil: atributos, alterações e uso na produção familiar. 2 ed. São Luís: Programa de Pós-graduação em Agroecologia/UEMA, v. 1, p. 53-69.

Rocha, H. R.; Golden, M. L.; Miller, S. D.; Menton, M. C.; Pinto, L. D.V. O.; Freitas, H.C.; Figueira, A. M. S. Seasonality of water and heat fluxes over a tropical Forest in eastern Amazônia. Ecological Applications. v. 14, p. S22-S32, 2004.

Salby, L.M., 1996. In: Fundamentals of Atmospheric Physics. International Geophysics Series, 61. Academic Press, San Diego.

Serafini, L.Z. Proteção jurídica das áreas úmidas e os direitos Socioambientais. Dissertação de Mestrado. Programa de Pós-Graduação em Direito da PUC-PR, Curitiba, 2007. Disponível em :<http://www.dominiopublico.gov.br/download/teste/arqs/cp024867.pdf >.

Silva, V. P. R.; Correia, A. A.; Coelho, M. S., 1998. Análise de tendência das series de precipitação pluvial do Nordeste do Brasil. Revista Brasileira de Engenharia Agrícola e Ambiental, Campina Grande, v.2, n.1, p.111-114.

Stanhill, G., Cohen, S., 2001. Global dimming: A review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences. Agric. For. Meteorol. 107, 255–278.

TrieB, Franz. Global potential of concentrating solar power. In: Conference Proceedings. 2009.

Varejão-Silva, M.A., 2006. Meteorologia e Climatologia. Versão digital 2. Recife, PB, março, 463p.

Weinrub, A., 2011. Decentralized Renewable Energy in California.

Wang, Shifeng; Koch, Barbara., 2010. Determining profits for solar energy with remote sensing data. Energy, v. 35, n. 7, p. 2934-2938.

Wild, M., Gilgen, H., Roesch, A., Ohmura, A., Long, C.N., Dutton, E.G., Forgan, B., Kallis, A., Russak, V., Tsvetkov, A., 2005. From dimming to brightening: decadal changes in solar radiation at earth's surface. Science 308, 847–850.