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Performance analysis of a grid connected photovoltaic system in northeastern Brazil

Lutero Carmo de Lima *, Leonardo de Araújo Ferreira, Francisco Hedler Barreto de Lima Morais

Mestrado Acadêmico em Ciências Físicas Aplicadas, Universidade Estadual do Ceará, Fortaleza, CE 60740-000, Brazil

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ABSTRACT

This article presents the performance analysis of a 2.2 kW_p photovoltaic system installed at the State University of Ceará, Fortaleza, Brazil (latitude 3.40°S, longitude 38.33°W and 31 m above sea level). The system was monitored from June 2013 to May 2014. In the measured period the annual energy yield was 1685.5 kWh/kW_p. The average daily reference, array and final yields of the system were 5.6 kWh/kW_p, 4.9 kWh/kW_p and 4.6 kWh/kW_p, respectively. The annual average daily array and system losses were 1.05 kWh/kW_p and the annual average array, system and inverter efficiencies were 13.3%, 12.6% and 94.6%, respectively. The performance ratio and capacity factor were 82.9% and 19.2%, respectively. These numbers highlight the relatively good performance of PV systems installed in the northeast region of Brazil.

Introduction

Energy is one of main ingredients for the development and maintenance of a modern society with benefits of its socio-economic and technological advancements. Providing energy for homes and buildings, agriculture, transportation, services, and industries in a sustainable way and at the same time guaranteeing resources for the future generations is the ultimate challenge for the humanity. As a result of greenhouse gases emissions from fossil fuels, their decline in reserves and consequent increasing price, and potential impacts on climate change, many countries are now reexamining their national energy policies with view of shifting toward low-carbon and renewable energy sources (Adaramola, 2015; Adaramola and Vagnes, 2015). Among the various forms of renewable energies such as wind energy, bioenergy and others, photovoltaic energy occupies a prominent position due to many peculiarities.

Economic incentives, reduction in cost, and the fast technological developments allow the use of grid connected photovoltaic plants in a simple, efficient and profitable way. The photovoltaic (PV) energy assumes, therefore, an increasing role within the spectra of the energy sources, especially for its simplicity of installation and integration in building architecture (Micheli et al., 2014). Consequently the global cumulative installed capacity of PV systems increased rapidly from about 1.3 GW in 2000 to 139 GW at the end of 2013 (Adaramola, 2015).

Brazil has an excellent level of solar radiation mainly in the northeast region. In its semi-arid region there is the best insolation, with typical values of 200 to 250 W/m^2 of continuous power which is equivalent the falling solar radiation from 1752 to 2190 kWh/m^2/year (Marques et al., 2009; Braga, 2008; Ruether and Zilles, 2011). Considering the country's advantageous solar radiation conditions, grid connected photovoltaics, with an installed capacity of only 4.5 MW_p in the year 2013, is still an unrepresented energy form in Brazil (Holdermann et al., 2014). Grid connected PV experience in Brazil is still limited to a handful of small installations operating at universities, research institutes (Ruether and Zilles, 2011), some private institutions (MPX for example), few in residences and commerce, at least in its northeast region. So it is important for the country to be prepared and to accumulate experience with grid connected PV in order to be able to make the most of distributed benefits of this benign technology when it becomes more cost-effective (Jannuzzi and de Melo, 2013).

Performance assessment of PV systems is the best way to determine the potential for PV power production in an area (Adaramola and Vagnes, 2015). Usually the performance of photovoltaic modules refers to Standard Test Condition (STC) which is not always representative for the real module operation (Micheli et al., 2014). PV module technology, weather conditions (incident radiation, temperatures), inclination, inverter and control systems, sun-tracker system, and wiring are factors which influence the performance of a PV system (Díez-Mediavilla et al., 2012). There are many performance evaluation studies of PV systems installed outdoors across Europe and globally as referenced by Adaramola and Vagnes (2015), Micheli et al. (2014), Díez-Mediavilla et al. (2012), Ayompe et al. (2011), Mpholo et al. (2015), Kumar et al. (2014), Padmavathi and Daniel (2013), to name a few. However Brazil and the Latin America are poorly represented in such studies although presenting an immense potential for its utilization (Dávi et al., 2016).

As highlighted by Ayompe et al. (2011), the performance assessment of a PV system include parameters calculation such as:

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* Corresponding author.
E-mail address: lutero.lima@uece.br (L.C. de Lima).

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annual energy generated, reference yield, array yield, final yield, array capture losses, system losses and cell temperature losses, PV module efficiency, system efficiency, inverter efficiency, performance ratio, and capacity factor. Results obtained will provide useful information to policy makers and interested individual and organization about actual performance of grid connected PV system in a region or country (Adaramola and Vagnes, 2015).

The state of Ceará located in the northeast cost of Brazil, in the semi-arid region, has a land extension of about 149,000 km^2 which correspond to 1.74% of the Brazil's territory and population of about 8.5 million inhabitants. Ceará has a considerable potential for renewable energies under the forms of solar, wind and biomass. The wind energy potential of Ceará is estimated in 35 GW and at the end of the present year it is expected to reach 1.8 GW of installed wind farms in operation. The average daily solar radiation in one square meter in Ceará reaching about 5.5 kWh is one of the highest in Brazilian territory. At the year 2011 the state launched a 1 MW private and commercial photovoltaic power plant in the city of Tauá, 350 km far from its capital, Fortaleza (Esteves et al., 2015). At the present time, the government of such state is improving regulatory framework in order to promote the increase in the insertion of photovoltaic systems in the domestic market. In the near future it is expected to reach 270 MW of installed photovoltaic systems (Jornal diário do nordeste, 2016).

The main objective of this article is to show the one year performance of a grid connected 2.2 kW$_p$ photovoltaic system installed at the State University of Ceará in the city of Fortaleza – Brazil.

The grid connected PV system

The grid connected PV system used in the present study is installed in the dependence of the Master Program on Applied Physics of the State University of Ceará, as shown in the Fig. 1. The system started operation on November, 2012. The University is located on the latitude 3.40°S and longitude 38.33°W, and about 31 m above sea level. The PV system consists of 18 modules covering a total area of 29 m^2 with an installed capacity of 4.4 kW$_p$. For the present study only 9 modules were used because of limitation on the number of available inverters. By this way the used system consists of 9 modules covering an area of 14.5 m^2 with an installed capacity of 2.2 kW$_p$. The Canadian Solar CS6P-245P of 245 W$_p$ modules were used. The modules were tilted at a fixed angle of 13° and oriented northward at an azimuth angle of 12°.

The SMA Sunny Boy SB 2500-HF-30 inverter was used for transforming the voltage from DC to AC and connected to the utility grid. The inverter had a rated maximum efficiency of 96.3% and maximum AC power of 2500 W. The sizing ratio which represents the ratio between the PV array installed capacity and the inverter capacity, in the present case, it was 0.9. The inverter was connected to the Sunny WebBox via a serial RS485 link. Data recorded on 5 min intervals in the WebBox was extracted via an SD card and read directly into a computer. Solar radiation, wind speed and ambient temperature were provided by an automatic Meteorological Station (50 m close to the PV system) of the FUNCEME – Ceará State Foundation for Meteorology and Water Resources.

Fig. 1. Picture of the PV array used.

Performance parameters

The performance of a grid connected PV system usually is evaluated taking as reference the IEC 61724 Standard. Evaluated parameters are: energy output, yields (reference yield, array yield and final yield), array and system energy losses, system efficiencies (array efficiency, system efficiency and inverter efficiency), performance ratio and capacity factor (Adaramola and Vagnes, 2015; Díez-Mediavilla et al., 2012; Ayompe et al., 2011; IEC, 1998; Ozden et al., 2017; Dobaria et al., 2016; Elhadj Sidi et al., 2016; Mpholo et al., 2015; Sundaram and Babu, 2015; Kumar et al., 2014; Sharma and Chandel, 2013; Padmavathi and Daniel, 2013; Wittkopf et al., 2012). Energy quantities are evaluated normalized to rated array power and referred to as yields which indicate the actual array operation relative to its rated capacity. System efficiencies are normalized to array area (Padmavathi and Daniel, 2013). These normalized performance parameters are relevant since they provide a basis under which grid tied PV systems can be compared under various operating conditions (Adaramola and Vagnes, 2015).

Energy output

The total energy is defined as the amount of alternating current (AC) power generated by the system over a given period of time. The total hourly, daily and monthly energy produced can be determined respectively as:

$$E_{AC,h} = \sum_{t=1}^{60} E_{AC,\ t} \tag{1}$$

$$E_{AC,d} = \sum_{h=1}^{24} E_{AC,\ h} \tag{2}$$

$$E_{AC,m} = \sum_{d=1}^{N} E_{AC,\ d} \tag{3}$$

where $E_{AC,t}$ is AC energy output at time t (in min); $E_{AC,h}$ is AC energy output at hour h; $E_{AC,d}$ is the daily AC energy output; $E_{AC,m}$ is the monthly AC energy output and N is the number of days in a month.

System yields

The system yields can be classified into three types which are array, final and reference yields. The yields indicate the actual array operation relative to its rated capacity. The array yield Y_A is defined as the direct current (DC) energy output from the PV array over a given period of time normalized by the PV rated power (Adaramola and Vagnes, 2015). It represents the time, measured in kWh/kW$_p$, that the PV array must be operating with its nominal power to generate the energy produced (Elhadj Sidi et al., 2016). It is given as:

$$Y_A = \frac{E_{DC}}{P_{PV,rated}} \quad (\text{kWh}/\text{kW}_p) \tag{4}$$

where E_{DC} is the DC energy output (kWh) from the PV array.

The final yield Y_F is defined as the total AC energy generated by the PV system for a defined period of time divided by the rated output power of the installed PV system (Sharma and Chandel, 2013). It indicates how many hours a day the PV system must operate at its rated power in order to produce the same amount of energy as was recorded. It is given as:

$$Y_F = \frac{E_{AC}}{P_{PV,rated}} \quad (kWh/kW_p) \tag{5}$$

where E_{AC} is the AC energy output (kWh).

The reference yield Y_R is the total in-plane insolation or global in-plane horizontal insolation divided by the reference irradiance under standard temperature conditions which is 1 kW/m^2. It is a measure of the theoretical energy available at a specific location over a specified time period. The reference yield can be calculated by:

$$Y_R = \frac{H_T}{H_R} \quad (kWh/kW_p) \tag{6}$$

where H_T is the in-plane solar radiation and H_R is the reference irradiance.

Array and system energy losses

The array capture losses L_A represent the losses due to array operation that highlight the inability of the array to fully utilize the available irradiance (Wittkopf et al., 2012). The array capture losses are the difference between the reference yield and the array yield. It is given as:

$$L_A = Y_R - Y_A \quad (kWh/kW_p) \tag{7}$$

The system losses L_S are as due to losses in converting the DC power output from PV to AC power by the inverter. It is given as:

$$L_S = Y_A - Y_F \quad (kWh/kW_p) \tag{8}$$

System efficiencies

The efficiency of a PV system can be grouped into PV array efficiency, system efficiency and inverter efficiency. Depending on the available data and desire level of resolution, these efficiencies can be determined on instantaneous, hourly, daily, monthly and annually bases. The array efficiency is based on the DC power output while the system efficiency is a function of the AC power output. The array efficiency η_{PV} represents the mean energy conversion efficiency of the PV array, which is the ratio of daily array energy output (DC) to the product of total daily in-plane irradiation and area of the PV array (Wittkopf et al., 2012). The PV module efficiency is calculated by the following equation:

$$\eta_{PV} = \frac{100 \times E_{DC}}{H_t \times A_m} \quad (\%) \tag{9}$$

where A_m = array area (m^2). The overall system efficiency represents the performance of the entire PV system installed and it is given as:

$$\eta_{SYS} = \frac{100 \times E_{AC}}{H_t \times A_m} \quad (\%) \tag{10}$$

The inverter efficiency is given as:

$$\eta_{INV} = \frac{100 \times E_{AC}}{E_{DC}} \quad (\%) \tag{11}$$

Performance ratio

The performance ratio (PR) indicates the overall effect of losses on a PV array's normal power output. The PR values indicate how close it approaches ideal performance during real operation and allows comparison of PV systems independent of location, tilt angle, orientation and their nominal rated power capacity (Padmavathi and Daniel, 2013; Ayompe et al., 2011). The PV system efficiency is compared with the nominal efficiency of the photovoltaic generator under standard test conditions. Performance ratio is defined as the ratio of the final energy yield of the PV system Y_F to the reference yield Y_R (Ozden et al., 2017):

$$PR = \frac{100 \times Y_F}{Y_R} \quad (\%) \tag{12}$$

Capacity factor

The capacity factor is a means used to present the energy delivered by an electric power generating system (Elhadj Sidi et al., 2016) and is defined as the ratio of AC energy produced by the PV system over a given period of time (usually one year) to the energy output that would have been generated if the system were operated at full capacity for the entire period. The annual capacity factor of the PV system is given by the following equation:

$$CF = \frac{E_{AC}}{P_{PV,rated} \times 8,760} \tag{13}$$

Results and discussion

Fig. 2 shows the monthly average produced electrical energy and the measured in-plane solar irradiation. The irradiation varied between the value of 1970.5 kWh in April 2014 and 2908.7 kWh in October 2013. The lowest value of solar radiation was inside the rainy season in Fortaleza and the highest value was during the dry summer period.

The lowest value of monthly produced electrical energy was 244.9 kWh by April 2014 and the highest produced energy in the measured period was 374.0 kWh by October 2013. In the period of 12 months it was produced 3708.2 kWh being the monthly average of 309.0 kWh. The final produced energy during the period divided by the rated power of the system is 1685.5 kWh/kW$_p$. In city such as Tiruchirappalli, India, the energy output is 1600 kWh/kW$_p$, in Malaga, Spain, is 1,339 kWh/kW$_p$, in Crete, Greece is 1336.4 kWh/kW$_p$, 1230 kWh/kW$_p$ in Calabria, Italy, 700 kWh/kW$_p$ in Netherlands, 730 kWh/kW$_p$ in Germany, 790 kWh/kW$_p$ in Switzerland, up to 1840 kWh/kW$_p$ in Israel and 1372 kWh/kW$_p$ in India (Mpholo et al., 2015).

During the dry period (June 2013 to March 2014) it is concentrated the highest values of produced electrical energy and during the rainy period in the months of April and May of 2014 it was verified the lowest values of produced energy of 244.9 kWh and 257.5 kWh, respectively.

The city of Fortaleza, capital of the state of Ceará, is located in the northeast region of Brazil and has a tropical savanna climate with dry winters. Over the course of a year, the temperature typically varies from 24 °C to 31 °C, being the annual average of 26.6 °C. Rarely its ambient temperature is below 22 °C or above 32 °C. The length of the day does not vary substantially over the course of the year, staying within 20 min of 12 h throughout. The shortest day is June 20 with 11:54 h of daylight and the longest day is December 21 with 12:20 h of daylight. From November to May is the period of clouds in Fortaleza being April 6 the cloudiest day of the year and August 28 the clearest day of the year. As can be seen in Fig. 2 in the period of clouds the electrical energy production of the PV system decreases and by coincidence April is the month where the PV system produced the minimum of electrical energy in the measured period and August was the second most productive month of electrical energy. On the other hand, the in-plane solar irradiation was the minimum in April and the maximum

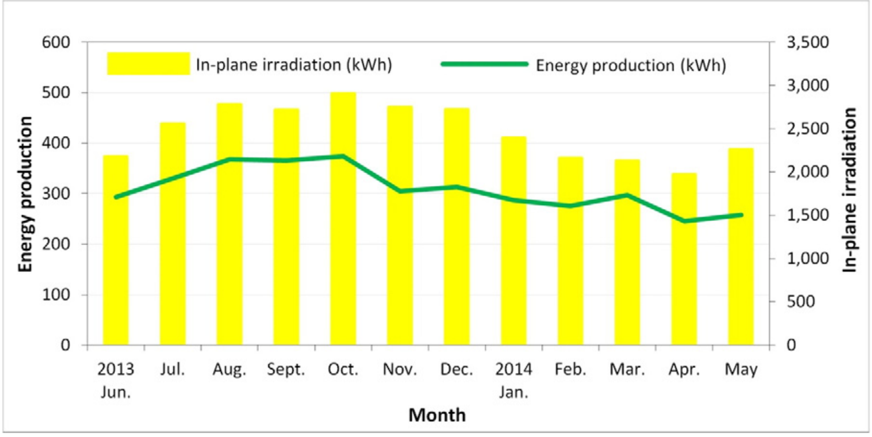

Fig. 2. Monthly energy production and in-plane irradiation.

in October. Precipitation shows the same statistical pattern of clouds in Fortaleza. However the wind speed strongly impacts the production of electrical energy in PV systems in Fortaleza. For example, over the course of a typical year wind speeds vary from 0 m/s to 9 m/s. The average daily maximum wind speed of 8 m/s occurs around October 5 declining very slowing during the months of August, September and November. The period of August to October is the most productive one of the here studied PV system. On the other hand, the least productive period comprehends the months of March, April and May where the lowest average wind speed is of 3 m/s (Weatherspark, 2016). Wind flow on PV modules contributes to the decrease of cells operating temperature. Higher wind speeds are beneficial to PV module operation because of the cooling effect on PV modules (Elhadj Sidi et al., 2016). In a typical day of October when the system presented its most productive period temperature of the back surface of one module, ambient temperature, levels of solar radiation, and wind speeds were measured. The ambient temperature varied from 27.2 °C to 32.1 °C, the module temperature varied from 29.1 °C to 45.5 °C, the maximum monitored solar irradiation was 1030 W/m^2, and the wind speed varied from 3.3 m/s to 6.9 m/s. The increase in the ambient temperature and module temperature was followed by the simultaneous increase in the level of solar radiation, as expected. The maximum difference of temperature between ambient and module was 14.4 °C with the solar radiation level of 800–899 W/m^2 and wind speed was around 6.1 m/s.

The output power of the PV system has a linear relationship with the solar radiation as shown in Fig. 3 and demonstrated by the correlation coefficient (R^2) of 0.9811. The equation which correlates the output electrical energy (E$_{AC}$) with solar radiation (H) is $E_{AC} = 0.1319\text{H} - 1.4260$. Equation obtained by Adaramola and Vagnes (2015) gives value about 5% higher than the present one. This difference is inside the range of experimental uncertainty. The importance of one equation such this is that it make possible to evaluate the energy output of a PV system just by only knowing the incident in-plane solar radiation. Ayompe et al. (2011) have also presented one of this equation although the difference between the equation of the present study and theirs is very considerable with values around 15% higher. It is supposed that such difference could be due to specific characteristics of each individual PV system and possibly two of them are components of different manufacturers and different climatic conditions.

The variation of the monthly average daily reference, array and final yields are shown in Fig. 4. It can be observed that the lowest values of them occurred in the rainy period and are 4.5 kWh/kW$_p$/day, 3.9 kWh/kW$_p$/day and 3.7 kWh/kW$_p$/day in April 2014, respectively. The highest observed values of reference yield of 6.5 kWh/kW$_p$/day was in the month October 2013, of array and final yields were 5.8 kWh/kW$_p$/day and 5.5 kWh/kW$_p$/day, for the month of September, respectively. The monthly averages for the period of one year of measurements were 5.6 kWh/kW$_p$/day, 4.9 kWh/kW$_p$/day and 4.6 kWh/kW$_p$/day, respectively. For all months of the monitored period, there is a practically constant difference between average array yield and system yield. This difference is due to DC/AC conversion losses produced in the inverter, showing that irrespective of the climatic conditions the inverter spent almost the same monthly energy to process conversion. This reasoning makes sense because as seen before the ambient temperature in Fortaleza varies from 24 °C to 31 °C during the course of a year. Vignola et al. (2008) observed that

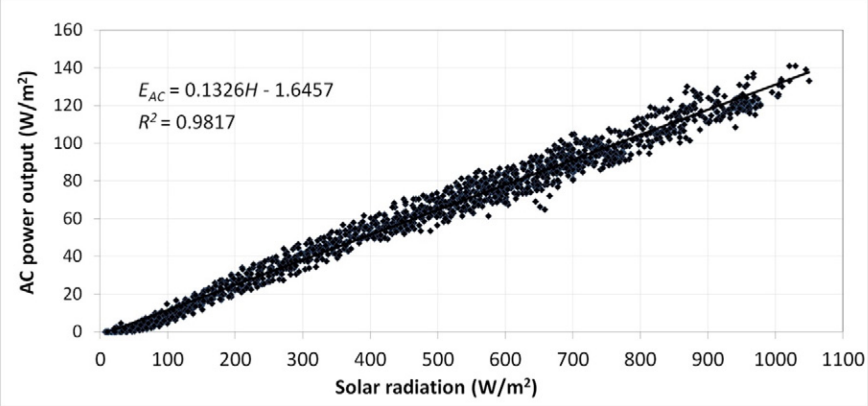

Fig. 3. AC output power of the PV system and solar radiation.

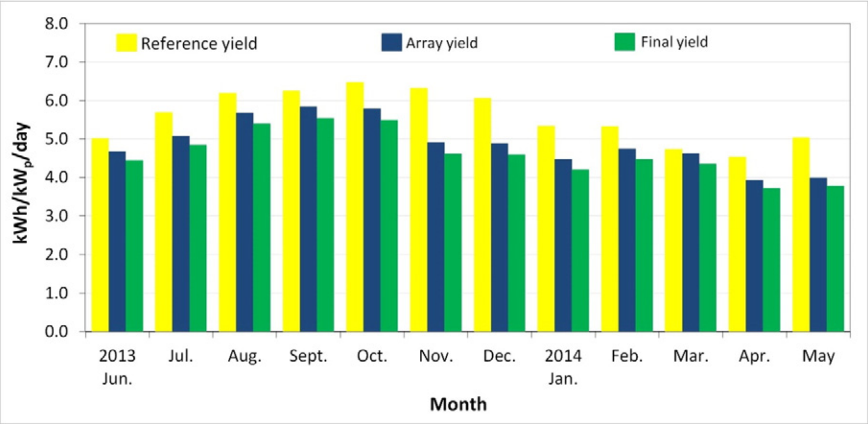

Fig. 4. Monthly average daily yields.

for about every 12 °C rise in ambient temperature the inverter efficiency falls about 1%.

The lowest values of yields are observed in the rainy period of the Brazilian northeast which is between months of February and May. Values observed between June and January are higher than values of the rainy period because of the dry climatic conditions and higher solar in-plane irradiation.

Comparing yield values of the present system with values of others studies, the average final yield of the present study was 4.6 kWh/kW$_p$/day being a value higher than the majority of values found in the literature. For example, in cities where the climatic conditions were relatively similar to the semi-arid of Brazil, as for example, Nicosia, Cyprus, the average final yield was 4.3 kWh/kW$_p$/day and in the city of Sawda, in Kuwait, with arid climate, the final yield was 4.5 kWh/kW$_p$/day (Adaramola and Vagnes, 2015).

Fig. 5 shows the monthly average daily array capture and system losses relative to reference yield. In the month of November it is observed the highest value capture losses in the array of 1.42 kWh/kW$_p$/day and the lowest value of 0.13 kWh/kW$_p$/day was observed in the month of March. These values correspond to 22.5% and 2.3% of the respective monthly reference yields. In a PV system installed in Rajkot, India, capture losses were 22.27% and 3.79% of the respective reference yields (Dobaria et al., 2016). For a system in Singapore number were 22.66% and 17.06% (Wittkopf et al., 2012). One of the factors that collaborated for the increase in the losses of array in the month of November was the influence of shadowing of a concrete post close to the PV system. Losses in the system varied from 0.21 kWh/kW$_p$/day in April to the value of 0.32 kWh/kW$_p$/day in October, as shown in Fig. 5. These numbers correspond to 5.7% and 4.2% of the respective reference yields. Corresponding values of 26.3% and 3.55% were found in PV system in Mauritania (Elhadj Sidi et al., 2016), 18.57% and 10.34% for system in Lesotho (Mpholo et al., 2015), 5.55% and 5.06% in Singapore (Wittkopf et al., 2012) and 21.23% and 2.89% in Ireland (Mondol et al., 2006). The maximum overall losses were verified in November with value of 1.71 kWh/kW$_p$/day and the minimum in March with the value 0.38 kWh/kW$_p$/day. These numbers correspond to 27.1% and 6% of the respective reference yields. The annual average array capture, system and overall losses were 0.71 kWh/kW$_p$/day, 0.27 kWh/kW$_p$/day and 1.05 kWh/kW$_p$/day, respectively.

The monthly average array, system and inverter efficiencies through the recording period are shown in Fig. 6. The monthly average values are 13.3%, 12.6% and 94.6%, respectively. The highest values of efficiencies in the array, system and inverter were 14.8% (in August), 13.9% (in August) and 95.3% (in July), respectively.

In the months of November, December and January, shadowing of the system caused reduction in the efficiencies of array and system, and possibly in the inverter efficiency. Shadowing of a concrete electrical grid post in the array caused this reduction in efficiencies in the referred months thus resulting in values such as 11.8% and 11.1% for the efficiencies of array and system, respectively. In those months the inverter efficiency remained around 94%, the lowest value.

In Fig. 7 it can be observed the monthly average daily performance ratio and capacity factor. The annual average performance ratio was 82.9% with the minimum value in November of 72.9% and the maximum value of 91.9% in March. Performance ratio is a measurement

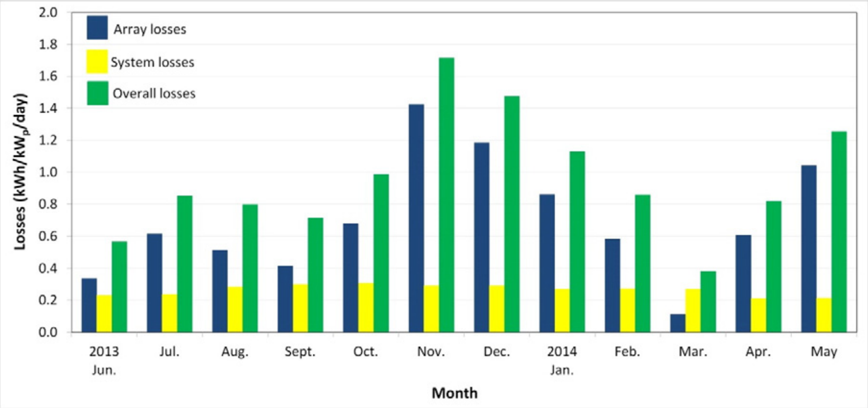

Fig. 5. Average daily array capture, system and overall losses.

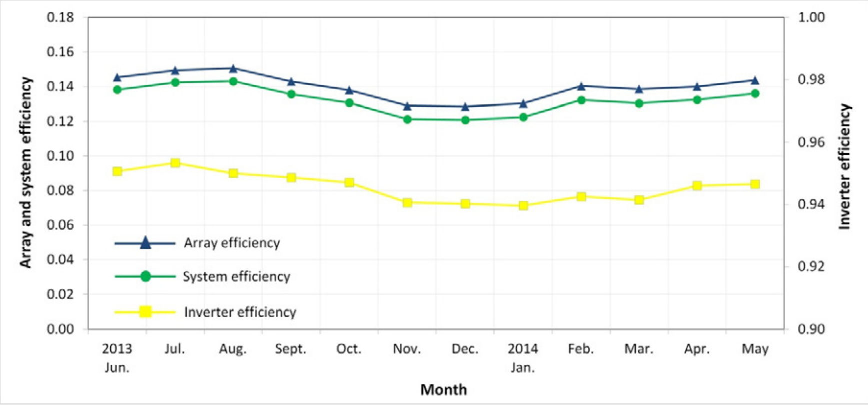

Fig. 6. Average array, system and inverter efficiencies.

index for how close a system approaches ideal performance during real operation (Mpholo et al., 2015). The performance of the present system accused decline in the months November, December and January due to shadowing of the concrete post, as already written before. The rainy season of March to May did show also decline in the performance ratio. In India performance ratio of different systems varies from 68% to 83% (Dobaria et al., 2016), from 55% to 94% (Kumar et al., 2014), from 60% to 78% (Padmavathi and Daniel, 2013), from 55 to 83% (Sharma and Chandel, 2013), and from 85.5% to 92.3% (Sundaram and Babu, 2015). In Mauritania it varies from 63.6% to 73.6% (Elhadj Sidi et al., 2016), in Lesotho it varies from 35% to 79% (Mpholo et al., 2015), and in Oman in desertic weather conditions the average performance ratio was 84.6% (Kazem et al., 2014). In Germany it varies from 38% to 88%, in Thailand it varies from 70% to 90% and in Poland from 50% to 80% (Mpholo et al., 2015). In Ireland it varies from 72.3% to 91.6% (Mondol et al., 2006). In Singapore it varies from 76% to 83% (Wittkopf et al., 2012). The variation of monthly performance ratio of Fortaleza is relatively close to some locations in India, Oman and Thailand.

The annual average capacity factor was 19.2%, with a minimum value of 15.5% in April and the maximum value of 23.1% in September. Capacity factor is the index that demonstrates the quantity of time in percentage which the production of the photovoltaic system operates in its highest capacity. Therefore the system produced in its maximum capacity approximately 70.2 days or 1684.5 h. The capacity factor, being a factor which has a direct implication on the cost of electricity generation, shows its maximum real value in somewhat less than 0.5 (Padmavathi and Daniel, 2013) or in a more precise reasoning the typical capacity factor for a PV system is in the range of 0.15 to 0.4 (Kazem et al., 2014). Therefore together with the performance ratio, capacity factor is a very important parameter to evaluate a grid connected photovoltaic system. In India, for example, capacity factor across the country varies between 16% and 20% (Padmavathi and Daniel, 2013). In Mauritania capacity factor varies from a minimum of 11.7% in winter to a maximum of 20.5% (Elhadj Sidi et al., 2016). In Lesotho the average is 17.2% ranging from 8.7% to 21% (Mpholo et al., 2015). In Malaysia a system presented capacity factor of 10.47% (Khatib et al., 2013). In Norway the annual average of one studied PV system was 10.6% (Adaramola and Vagnes, 2015) and 10.1% for a system in Dublin (Mondol et al., 2006).

Conclusions

In this article, the 2.2 kW_p grid connected photovoltaic system installed at the State University of Ceará – Brazil was studied from June 2013 to May 2014 and its performance parameters were determined. The total output energy during the measured period was of 3708,2 kWh and the rated energy output was 1685.5 kWh/kW_p. The daily average reference, array and final yields, the array capture, system and overall losses, the array, system and inverter efficiencies, the performance ratio and the capacity factor varied from a minimum to a maximum values of 4.5 kWh/kW_p–6.5 kWh/kW_p, 3.9 kWh/kW_p–5.8 kWh/kW_p, 3.7 kWh/kW_p–5.5 kWh/kW_p, 0.13 kWh/kW_p–1.42 kWh/kW_p, 0.21 kWh/kW_p–0.32 kWh/kW_p, 0.38 kWh/kW_p–1.71 kWh/kW_p, 11.8%–14.8%, 11.1%–13.9%, 94%–95.3%, 72.9%–91.9% and 15.5%–23.1%, respectively. The monthly average values for the entire period of measurements were 5.6 kWh/kW_p, 4.9 kWh/kW_p, 4.6 kWh/kW_p, 0.71 kWh/kW_p, 0.27 kWh/kW_p, 1.05 kWh/kW_p, 13.3%,

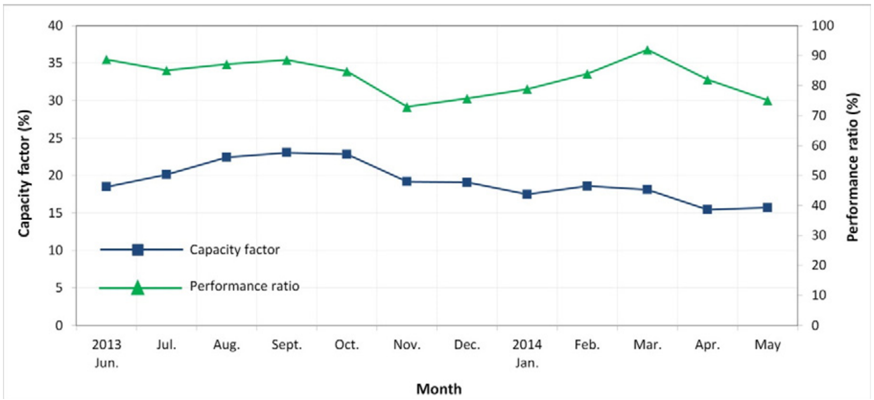

Fig. 7. Average performance ratio and capacity factor.

12.6%, 94.6%, 82.9% and 19.2%, respectively. These numbers could be better if the here studied PV system didn't suffer the shadow interference of a concrete post during the months of November, December and January. Notwithstanding performance results show the good potential of producing electricity through photovoltaic solar energy in the state of Ceará – Brazil.

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References

Adaramola MS. Techno-economic analysis of a 2.1 kW rooftop photovoltaic-grid-tied system base on actual performance. Energy Convers Manag 2015;101:85–93.

Adaramola MS, Vagnes EET. Preliminary assessment of a small-scale rooftop PV-grid tied in Norwegian climatic conditions. Energy Convers Manag 2015;90:458–65.

Average Weather for Fortaleza, Brazil. https://weatherspark.com/averages/33419/Fortaleza-Ceara-Brazil, 2016.

Ayompe LM, Duffy A, McCormack SJ, Conlon M. Measured performance of a 1.72 kW rooftop grid connected photovoltaic system in Ireland. Energy Convers Manag 2011;52:816–25.

Braga Renata Pereira. Energia solar fotovoltaica: fundamentos e aplicações. 2008. 80 f. TCC (Graduação) - Curso de Engenharia Elétrica. Rio de Janeiro: Escola Politécnica, Universidade Federal do Rio de Janeiro; 2008. [(in portuguese). Available in: <http://monografias.poli.ufrj.br/monografias/monopoli10001103.pdf>; 2008 [Accessed in 10.09.2016]].

Dávi GA, Caamano-Martín E, Ruether R, Solano J. Energy performance evaluation of a net plus-energy residential building with grid-connected photovoltaic system in Brazil. Energy Build 2016;120:19–29.

Díez-Mediavilla M, Alonso-Tristán C, Rodríguez-Amigo MC, García-Calderón T, Dieste-Velasco MI. Performance analysis of PV plants: optimization for improving profitability. Energy Convers Manag 2012;54:17–23.

Dobaria B, Pandya M, Aware M. Analytical assessment of 5.05 kW$_{p}$ grid tied photovoltaic plant performance on the system level in a composite climate of Western India. Energy 2016;111:47–51.

Elhadj Sidi CEB, Ndiaye ML, Bah ME, Mbodji A, Ndiaye A, Ndiaye PA. Performance analysis of the first large-scale (15 MW$_{p}$) grid-connected photovoltaic plant in Mauritania. Energy Convers Manag 2016;119:411–21.

Esteves NB, Sigal A, Leiva EPM, Rodriguez CR, Cavalcante FSA, de Lima LC. Wind and solar hydrogen for the potential production of ammonia in the state of Ceará – Brazil. Int J Hydrogen Energy 2015;40:9917–23.

Holdermann C, Kissel J, Beigel J. Distributed photovoltaic generation in Brazil: an economic viability analysis of small-scale photovoltaic systems in the residential and commercial sectors. Energy Policy 2014;67:612–7.

IEC Standard 61724. Photovoltaic system performance monitoring-guidelines for measurement, data exchange and analysis; 1998.

Jannuzzi GM, de Melo CA. Grid-connected photovoltaic in Brazil: policies and potential impacts for 2030. Energy Sustain Dev 2013;17:40–6.

Jornal diário do nordeste. (in portuguese). Available in: http://diariodonordeste.verdesmares.com.br/cadernos/negocios/projetos-de-energia-solar-no-ce-somam-270-mw-1.1477088, 2016. [Accessed in 10.09.2016].

Kazem HA, Khatib T, Sopian K, Elmenreich W. Performance and feasibility assessment of a 1.4 kW roof top grid-connected photovoltaic power system under desertic weather conditions. Energy Build 2014;82:123–9.

Khatib T, Sopian K, Kazem HA. Actual performance and characteristic of a grid connected photovoltaic power system in the tropics: a short term evaluation. Energy Convers Manag 2013;71:115–9.

Kumar KA, Sundareswaran K, Venkateswaram PR. Performance study on a grid connected 20 kW$_{p}$ solar photovoltaic installation in an industry in Tiruchirappalli (India). Energy Sustain Dev 2014;23:294–304.

Marques RC, Krauter SCW, de Lima LC. Energia solar fotovoltaica e perspectivas de autonomia energética para o nordeste brasileiro. Rev Tecnol 2009;30:153–62.

Micheli D, Alessandrini S, Radu R, Casula I. Analysis of the outdoor performance and efficiency of two grid connected photovoltaic systems in northern Italy. Energy Convers Manag 2014;80:436–45.

Mondol JD, Yohanis Y, Smyth M, Norton B. Long term performance analysis of a grid connected photovoltaic system in Northern Ireland. Energy Convers Manag 2006;47:2925–47.

Mpholo M, Nchaba T, Monese M. Yield and performance analysis of the first grid-connected solar farm at Moshoeshoe I International Airport, Lesotho. Renew Energy 2015;81:845–52.

Ozden T, Akinoglu BG, Turan R. Long term outdoor performance of three different on-grid PV arrays in central Anatolia – an extended analysis. Renew Energy 2017;101:182–95.

Padmavathi K, Daniel SA. Performance analysis of a 3 MW$_{p}$ grid connected solar photovoltaic power plant in India. Energy Sustain Dev 2013;17:615–25.

Ruether R, Zilles R. Making the case for grid-connected photovoltaics in Brazil. Energy Policy 2011;39:1027–30.

Sharma V, Chandel SS. Performance analysis of a 190 kW$_{p}$ grid interactive solar photovoltaic power plant in India. Energy 2013;55:476–85.

Sundaram S, Babu JSC. Performance evaluation and validation of 5 MW$_{p}$ grid connected solar photovoltaic plant in South India. Energy Convers Manag 2015;100:429–39.

Vignola F, Mavromatakis F, Krumsick J. Performance of inverters. Proc. of the 37th ASES Annual Conference, San Diego, CA; 2008.

Wittkopf S, Valliappan S, Liu L, Ang KS, Cheng SCJ. Analytical performance monitoring of a 142.5 kW$_{p}$ grid-connected rooftop BIPV system in Singapore. Renew Energy 2012;47:9–20.