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Performance Analysis of a Photovoltaic System installed in the Northeast of Brazil

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***Keywords*— Diversity management, diversity, Identity, Stereotype.**

***Abstract*— *This article shows the study about the photovoltaic solar power plant installed in Messejana, Fortaleza, Ceará, Brasil (latitude 3° 49'57",7" S and longitude 38°29'58",3'' W) with an installed capacity of 19.2 kWp. It aims to punctuate the good practices for correct sizing of a grid connected photovoltaic power system, in microgeneration, and evaluate the system performance. The monitoring of the system was between March and September 2021. During this measuring period, the energy delivered to the power grid was 18197.15 kWh. the average reference, array, and final yields were 5.45 kWh/kWp, 4.33 kWh/kW, and 4.26 kWh/kW, respectively. The annual loss of the array and the system were 0.81 kWh/kW and 0.07 kWh/kWp, respectively, and the annual average of array and system efficiencies were 15.13% and 14.88%, respectively. The performance rate and capacity factor were 81.85% and 18.05%, respectively. Those numbers highlight the relatively good performance of photovoltaic systems installed in the Northeast region of Brazil.*

I. INTRODUCTION

Given the current scenario of electric energy consumption and considering the fact that energy is a fundamental subsidy for human activities and is used in different fields and spatialities, the use of renewable energy sources is increasing and gaining strength in the global energetic scenario. The advantage of energy generation through renewable sources is mainly the minimum impact on the environment (Jung, 2015).

The use of solar radiation for energy generation has advantages compared to the other sources since it receives economic incentives, has low maintenance costs, and is an inexhaustible resource. Based on this, it is necessary to invest in research and innovation in the Photovoltaic Energy sector and seek improvements in the modules and system performance.

Besides the previously mentioned advantages, the consumer has the possibility to lower the energy bill. This occurs when the amount of energy generated by the system is equal to or higher than the energy consumed in the same period. This way, the consumer receives credits that can be used later. According to the laws of the National Electric Energy Agency (Agência Nacional de Energia Elétrica - ANEEL), the credits are valid for 60 months and can be used to reduce the consumption of consuming units belonging to the same owner but located in a different area, as long as the said area is inside the attendance area of the same distributor. This type of use is what the agency calls "remote self-consumption" (ANEEL, 2015).

According to CRESESB (2008), every year the Earth receives solar energy equivalent to 10 thousand times the global energetic consumption in the same period. Great regions in Brazil receive more than 2200 hours of insolation per year, which is equivalent to 32 thousand times the electricity consumed nationally in 2015 (WANDERLEY, 2016). Considering these numbers and information, it is possible to conclude that the use of photovoltaic energy in Brasil is very viable.

The performance evaluation of photovoltaic systems is the best way to determine the potential of photovoltaic energy production in an area. Normally, the performance of photovoltaic modules refers to the standard test conditions (STC), which do not always represent the real module operation (LIMA, et al, 2017).

There is a possibility of loss in the power generation of the solar system by different factors, such as loss due to shadowing, inclination, misdirection or poor location, lack of cleaning of the panels, or maintenance of the cables and inverter, among others.

All the mentioned factors might damage or shorten the lifespan of the system or cause it to have performance below expected. That being said, it is necessary to take specific measurements to avoid possible losses and, thus, preserve the system.

The system connected to the power grid

The panels used were from DAH Sola, model HCM72X9-400W, made of monocrystalline silicon with nominal power of 400 Wp, providing energy for two Growatt inverters model 8000MTL-S that, together, had a nominal power of 16 kWp. These pieces of equipment are in a commercial building in Messejana, Fortaleza-CE, coordinates 3°49′57,7″ latitude south and 38°29′58,3″ longitude west. It is a system connected to a power grid that started operating in January 2021.

The panels point to the geographic north, as recommended for installations located on the south of the Equator line, and with an inclination that follows the roof of the building. The recommendation for maximum production throughout the year is to install the panels with an inclination similar to the latitude of the place. The grid-connected photovoltaic power system (GCPVS) has 6 strings of 8 panels each, with a total of 48 photovoltaic panels with an installed power of 19,2 kWp and a total area equals 105.6 m². The calculated area of unit power (kWp) was 5.5 m².

Fig.1: Image of the 19.2 kwp Solar System

Source: Author.

Performance Analysis of the Photovoltaic Systems

The performance evaluation of a grid-connected photovoltaic power system normally uses as a reference the IEC 61724:1998 pattern and ABNT NBR 16274/2014 norm. The evaluated indicators are Total Energy, the yield of the photovoltaic system (of reference, PV array, and final), losses of system energy and of the system itself, system efficiency (set efficiency, system efficiency, and inverter efficiency), Performance rate, and Capacity factor (LIMA et al., 2017).

Total Energy

The total energy is the amount of alternated potency generated by the system for a certain amount of time. The total, daily, and monthly hourly energy produced might be determined respectively by:

$$E_{CA,h} = \sum_{t=1}^{60} E_{CA,t} \quad (1)$$

$$E_{CA,d} = \sum_{h=1}^{24} E_{CA,h} \quad (2)$$

$$E_{CA,m} = \sum_{d=1}^{N} E_{CA,d} \quad (3)$$

In which, E_{ACt} is the total AC energy at t time (in minutes), E_{ACh} is the hourly total AC energy (in hours), $E_{AC,d}$ is the daily total AC energy, $E_{AC,m}$ is the monthly total AC energy, and N is the number of days on the month.

Photovoltaic system yield

The photovoltaic system productions are represented by the letter "Y" and classified in three types: reference yield (Y_R), PV array yield (Y_{PV}), and final yield (Y_F). It represents the energy generated by the system, in kWh, for each KW_P of installed power. The used unit is kWh/KW_P in day or hours/day. When expressed in hours/day, it represents the time that the system should operate in its nominal power to generate the same amount of energy on the same given period of time (MORAIS, 2017).

The yields indicate the real operation of the photovoltaic panels and the photovoltaic array in relation to its nominal power (MORAIS, 2017).

The PV array yield (Y_{PV}) is given by equation 4, in which de E_{DC} is the total energy (in kWh) produced by the photovoltaic array:

$$Y_{FV} = \frac{E_{cc}}{E_{cc.nom}} \left(\frac{kWh}{kW_P \,.\, dia}\right) \tag{4}$$

The final yield Y_F is given by equation 5, in which E_{AC} is the total AC energy:

$$Y_F = \frac{E_{CA}}{P_{FV.nom}} \left(\frac{kWh}{kW_P \,.\, dia}\right) \tag{5}$$

The reference yield Y_R is the total irradiation on the level or global horizontal irradiation (H_T) on the level divided by the reference irradiation (H_R) in standard temperature and pressure conditions are equal to 1 kWh/m^2. This is a theoretical energy measurement available in a specific place during a specific period of time (MORAIS, 2017). The reference performance can be calculated by equation 6:

$$Y_R = \frac{H_T}{H_R} \left(\frac{kWh}{kW_P \,.\, dia}\right) \tag{6}$$

According to equations 4, 5, and 6, we will reach values that theoretically express a mathematical relation between the productivities, it is possible to affirm that:

$$Y_R \geq Y_{FV} \geq Y_F \tag{7}$$

Losses

Captures losses of the photovoltaic array (L_{PV}) represent the losses due to the operation that highlight the incapacity of the photovoltaic array in fully using the available irradiation. The calculation of the PV array capture loss is the difference between the reference production of the photovoltaic panels (MORAIS, 2017). It is given by equation 8:

$$L_{FV} = Y_R - Y_F \left(\frac{kWh}{kW_P}\right) \tag{8}$$

The losses of photovoltaic system (L_S) are due to the losses on the conversion of direct current output (E_{DC}) to alternating current (E_{AC}) by the inverter, it is the subtraction of the PV array yield by the final yield. It is also necessary to consider the losses by the Joule effect. Equation 9 below shows it:

$$L_S = Y_{FV} - Y_F \left(\frac{kWh}{kW_P}\right) \tag{9}$$

The total PV system losses (L_T) are the sum of the capture loss of the PV array (L_{PV}) with the PV system losses (L_S), given by equation 10 below:

$$L_T = L_{FV} + L_S \left(\frac{kWh}{kW_P}\right) \tag{10}$$

Photovoltaic system efficiencies

There are three classifications for the photovoltaic system efficiency: photovoltaic array efficiency, system efficiency, and inverter efficiency. Depending on the available data and the level of desired resolution, these efficiencies might be determined in instant, hourly, daily, monthly and annual basis, expressed in percentages (MORAIS, 2017).

The PV array efficiency is the output of DC energy while the system efficiency is a function of the output of AC energy. The PV array efficiency (η_{PV}) represents the average efficiency of the energy conversion of the photovoltaic array, which is the ratio between the daily production of DC energy and the product of total daily irradiation on the level and the area of the PV array (LIMA *et al*., 2017). The PV array efficiency is calculated by equation 11, the system efficiency by equation 12, and the inverter efficiency by equation 13. Considering A_{PV} as the total area of the photovoltaic array in m^2:

$$\eta_{FV} = \frac{100 \ x \ E_{CC}}{H_T \ x \ A_{FV}} \ (\%) \tag{11}$$

$$\eta_{SYS} = \frac{100 \ x \ E_{CA}}{H_T \ x \ A_{FV}} \ (\%) \tag{12}$$

$$\eta_{INV} = \frac{100 \ x \ E_{CA}}{E_{CC}} \ (\%) \tag{13}$$

Capacity factor X "Performace ratio"

Capacity factor

The capacity factor is the "capacity that a system would have of producing energy if it operated in its full nominal power for the 24 hours of the day". The following equation shows the calculation of the annual capacity (SECUNDE, 2015):

$$FC\ (\%) = \frac{Eg(kWh)}{P_n\ (kWh)\ x\ 24h\ x\ 365} x100 \tag{14}$$

In which:

FC = System capacity factor;

Eg = energy produced by the system in a year;

P_n = nominal power of the photovoltaic system.

Performance Ratio – PR

Performance ratio (PR) is one of the most important variables when evaluating the efficiency of a GCPVS. In this analysis, it is possible to find the quality factor for the system. PR, indicated in percentage (%) shows the relationship between the real and theoretical outputs of the GCPVS, showing the percentage of available energy to inject on the grid after the deduction of the energy losses (related to the temperature of the operation of the PV modules, wiring, DC/AC energy conversion on the inverter, shadowing, among others) and the energy consumption for the operation.

The closer to 100% the PR is, the lower the system losses are, but it is not possible to reach a 100% PR level in practice, since there are inevitable losses during the operation of a PV system.

Equation y shows the calculation of the PR:

$$PR = \frac{YF}{\frac{\int_{t1}^{t2} Icol\, dt}{I_R}} \quad (15)$$

In which:

Icol = global irradiation received on the collector level;

IR = reference irradiation;

YF = system yield.

For a certain time interval, the calculation of the system yield is the relation between the average value of energy delivered to the load and the nominal power of the photovoltaic generator. The equation below shows how to calculate the system yield (SECUNDE, 2015).

$$YF = \frac{\int_{t1}^{t2} P_{Saida} \times dt}{P_{FV}^{0}} \quad (16)$$

In which YF is in kWh/kWp, or per hour. Therefore, though having more than one mechanism to evaluate the performance of photovoltaic systems, PR is, among other, the most commonly used for performance evaluation.

(Theoretical) energy production of a GCPVS

According to Morais (2017), it is possible to calculate the theoretic value of the energy produced by a GCPVS (E_{TCA}) following equation 17.

$$E_{CAT} = P_{FV,nom}\, x\, \frac{H_T}{H_R}\, x\, FS\, x\, PR\, x\, \eta_{INV} \quad (17)$$

In which E_{TAC} is the theoretical AC in kWh, $P_{PV,nom}$ is the GCPVS installed potency, H_T is the global irradiance (monthly or annual total), H_R is the reference irradiance in standard temperature and pressure conditions and are equal to 1 kW/m^2, *SF* is the shadowing factor, *PR* is the theoretical performance relation for the system and η_{INV} is the inverter efficiency. The *SF* varies from zero (0) to a total shadowing to one (1) when there is no shadowing.

II. RESULTS

The analysis used data from the datalogger of the Growatt inverter and pyranometer (PDC/FUNCEME). After extracting and compiling the data on an Excel sheet, it was possible to analyze the statistical data and produce the charts to enable comprehension and discussion. The data included on the inverter screen include DC power, DC tension, DC potency, AC power, AC tension, AC potency, and energy sent to the grid while the ShinePhone application shows potency and energy. The data are stored on a webserver or SD card every 30 minutes and, from this data, it was possible to determine the daily, monthly, and annual indicators. FUNCEME provides the irradiance data on an Excel sheet.

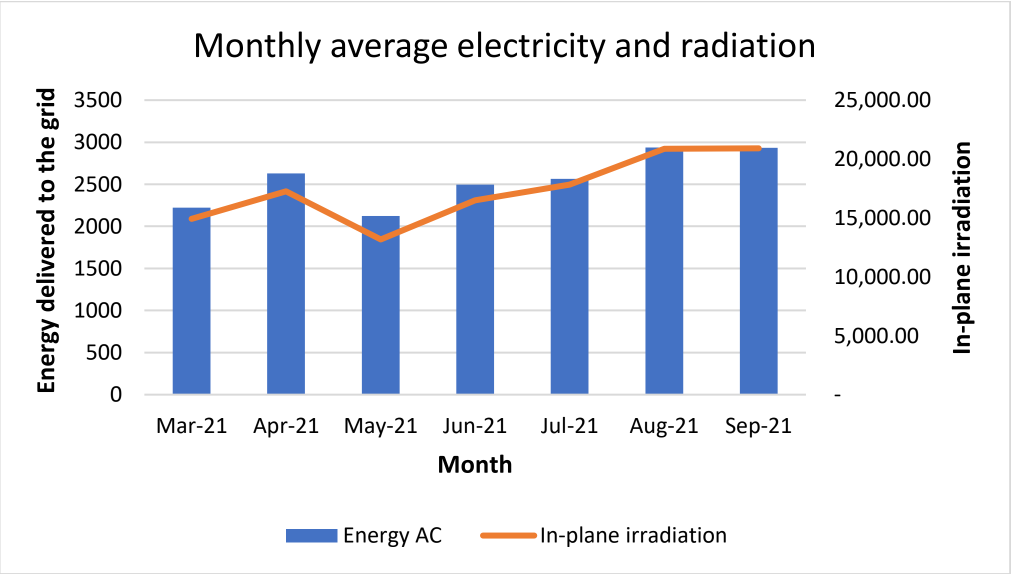


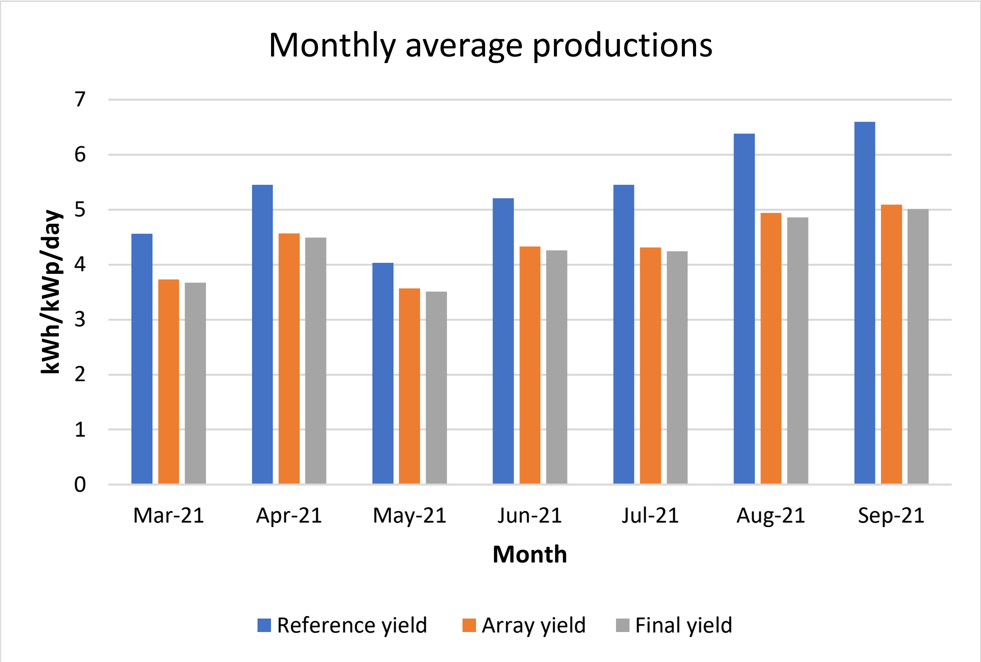
Fig.2 – Energy produced by the photovoltaic system and radiation on the horizontal level

Source: author

The analysis of the photovoltaic systems in this study covers the period from March to September 2021. According to the chart in Figure 2, the total energy sent to the grid from March 1, 2021, to September 30, 2021, was 18197 MWh with a monthly average of 2605.6 kWh. The maximum value of energy sent was in August/2021 (2986,89 kWh) and the lowest was in May/2021 (2157.82 kWh). For comparison purposes with the energy sent to the grid, we converted the irradiation measured in em kWh/m2 by direct rule of three with the total area of the photovoltaic panels (105.6 m²) to obtain the daily and monthly kWh values.

The highest solar irradiation value was in September/2021, during the dry season, without rain. In March/2021 and May/2021, there was a reduction in irradiation value with registered numbers of 14.921 kWh and 13.176 kWh, respectively.

The energy productions are in Figure 3. The daily annual average reference yield (YR), PV array yield (YPV), and final yield (YF) were 5.45 kWh/kWp.day; 4.33 kWh/kWp.day; 4.26 kWh/kWp.day, respectively.



Source: author.

The monthly average efficiencies for the photovoltaic system are in Figure 4. The inverter efficiency, found on the technical file by the manufacturer Growatt, is 98%.

The average efficiency from March/2021 to September/2021 of the photovoltaic array during the collection period was 15.13%, varying from 14,26% in September/2021 to 16.38% in May/2021. This article did not intend to analyze the degree of soiling on the PV modules, but it is possible to preliminarily conclude that the highest efficiency value of the array was during the period with more precipitation, which washed the panels.

The monthly average capacity factor (CF) varied between 14.86% (May/2021) and 21.22% (September/2021) and measures the average percentage in which the GCPVS worked at full capacity. The performance ratio (PR) varied between 77.15% in September/2021 to 88.63% in May/2021. The performance ratio (PR) measures the global effect of the losses over the nominal power of the GCPVS due to factors such as inefficiency of the inverters and losses on the conversion from DC to AC, soiling of the panels and failure of the components of the system, and lack of electric energy from the distributor (ENEL) which avoids the binding of the GCPVS. Figure 5 shows the monthly average CF and PR data.

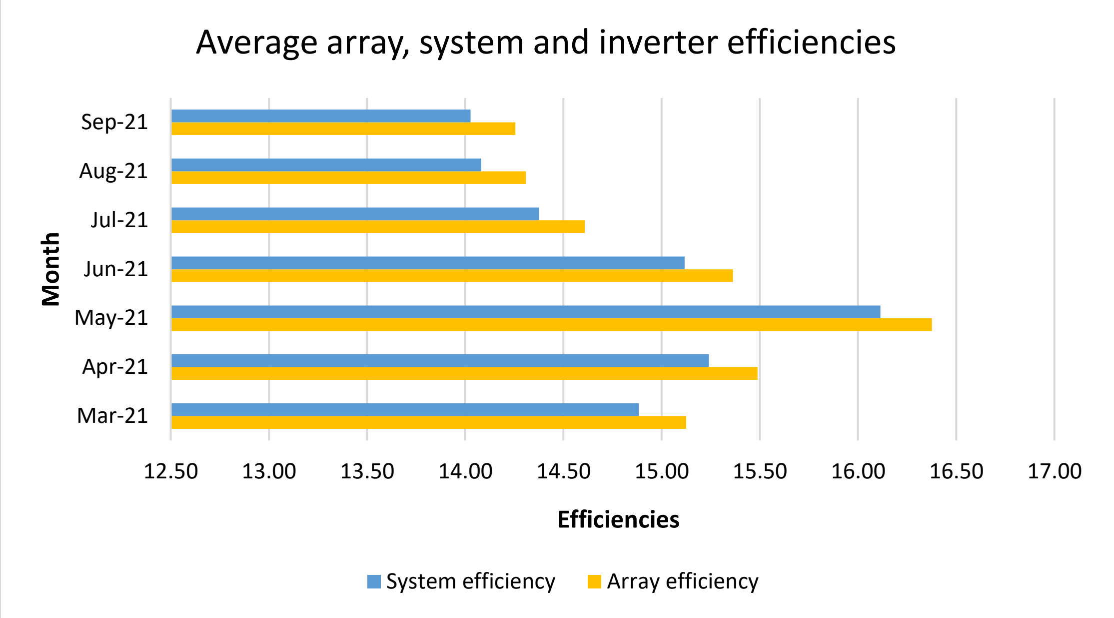


Fig.4 – Monthly average efficiencies

Source: author.

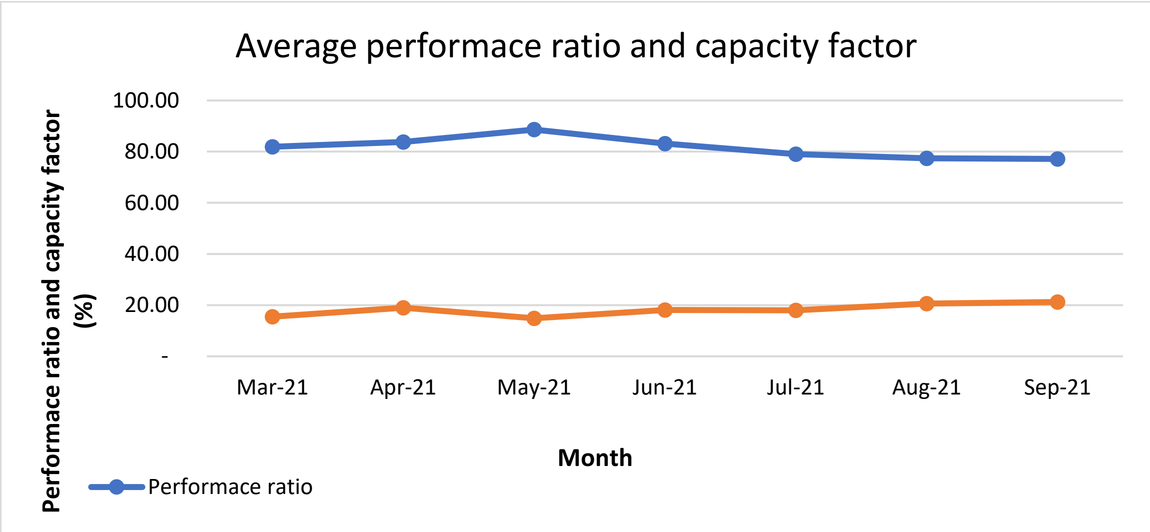


Fig.5 – Monthly averages: CF and PR

Source: author.

Figure 6 shows the relative losses of the analyzed GCPVS. The month with the highest loss was September/2021, with a value of 1.5 kWh/kWp.day, and the lowest was in May/202, 0.45 kWh/kWp.day. In all the months analyzed in this study, the PV array surpassed the system losses. According to Pinho and Galdino (2014), there is an optimization of the annual energy production of GCPVS with a fixed array when it points to the geographic north (azimuth 0) and has an inclination similar to the installation site. The annual average total loss for the GCPVS was 0.88 kWh/kWp.day.

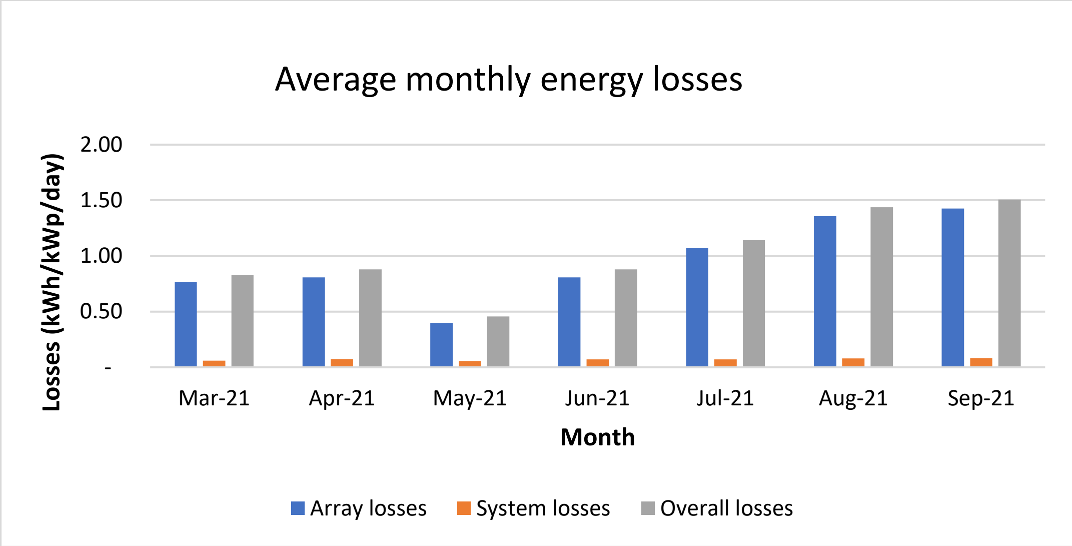


Fig.6 – Relative losses

Source: author.

III. CLOSING REMARKS

In this study, we analyzed a photovoltaic system connected to a 19.2 kWp grid installed in Messejana, Fortaleza, Ceará – Brasil from March 2021 to September 2021. The average energy delivered generated by the photovoltaic array in this period is 2563.6 kWh. The average reference, array, and final yields are 5.45, 4.33, and 4.26, respectively. The average array and system efficiencies are 15.13% and 14.88%, respectively, while the capacity factor and performance ratio averages are 18.05% e 81.85%, respectively. The total losses of the system are average 0.88 kWh/kWp/day. These results show a great performance of the analyzed system, indicating a good energetic potential of solar energy in Ceará - Brasil and also indicating that the localization of the system is in a shadowing-free environment and its installation project followed the proper guidelines.

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