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Analysis of PV Systems Installed in Paraná

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HIGHLIGHTS

- Comparative study of the operation of eight real cases of systems installed in Paraná.
- There is a convergence between the values estimated by the Atlas and the ones calculated.
- It was possible to identify the cities that presented the greatest figures of merit.

Abstract: With the development of renewable energies in the world, there is also an increase in solar photovoltaic systems globally. In Brazil, and in the state of Paraná, there is an exponential growth of this form of energy generation, which causes the necessity to study the performance of the installed systems. Therefore, this article analyzed eight photovoltaic systems installed in the state of Paraná, under the aspect of figures of merit parameters, through calculations of final yield, performance ratio and capacity factor. In addition, the calculated values were compared to the values estimated by the Solar Energy Atlas of the State of Paraná. As a result, the largest average differences in final yield, between the calculations and the Atlas, were found in the cities of Cascavel, while the smallest were observed in Goioerê.

Keywords: renewable energy; grid-connected photovoltaic systems; performance parameters.

INTRODUCTION

The worldwide development of renewable energy is increasing as a result of the concern about the effects of using conventional sources of energy generation and the demand for clean and more efficient sources of energy. Within this context, one of the most widely used renewable sources is photovoltaic (PV) energy, which is obtained from solar radiation [1-2].

As a result, in the end of 2019, the installed capacity of PV energy in the world was 627 GW, also, PV energy has become the fastest-growing energy source in the world, with an increase of 115 GW in only one year. Following the global trend, increases in the employment of this form of energy generation were observed in Latin America, mainly due to favorable policies and the abundance of solar resources [3].

In Brazil, the use of PV energy began to grow stronger in 2012, while on a global scale this growth started in 2006. This fact is related to normative resolution number 482 of 2012, which made possible the use of micro and mini-generation for small residential consumers and large manufacturers. Before that, the use of PV generation was restricted only to large generation plants and universities, mostly for research purposes [4]. The normative resolution number 482 also created the “Electricity Compensation System”, in which consumers are allowed to inject the surplus energy generated in the concessionaire's grid and consume the energy from the grid when there is no generation from PV plant [5].

Due to this fact, the installation of grid-connected photovoltaic systems (GCPVS) has been growing exponentially in Brazil, including Paraná. In 2019, 119.904 new PV systems were installed in Brazil, and 10.338 in Paraná. Besides, in 17th July of 2020 the PV installed capacity in Brazil was 3,12 GW, and in Paraná was 271,83 MW [6].

Monitoring these systems is important to ensure their proper functioning and to study their performance. Thus, this article analyzes the performance parameters of eight GCPVS installed in the State of Paraná.

MATERIAL AND METHODS

For the data analysis, eight GCPVS were chosen in western Paraná. The cities are: Cascavel, Goioerê, Ubiratã and Rancho Alegre D'Oeste. These systems were chosen due to the availability of access to their data. Each of these systems has a particularity, as they have different installed capacity. In addition, regarding the installation method, not all are installed in ideal conditions, where the PV panels must be installed facing north and inclined at the same angle as the installation location’s latitude. Another important fact is that the eight systems do not have the same uptime, so the calculations will take from one to twelve months, depending on the system.

To evaluate the systems, figures of merit are used to analyze their operation and explore the differences between each one. This type of tool allows comparing systems, even if they are in different places and with different nominal capacity [7].

The Final Yield (YF) is a figure of merit that compares the energy generated between systems due to standardized parameters, that is, it is possible to visualize which one is the most productive in terms of an installed power unit [7]. In Equation 1, it is observed how the YF is calculated, expressed in kilowatt-hours (kWh) per kilowatt peak (kWp).

$$YF = \frac{\text{energy generated}}{\text{installed power}} \tag{1}$$

The Performance Ratio (PR) configures the solar energy available in the plane of the PV panel that will be converted into electricity. This figure of merit considers losses in the conversion process, such as inverters, cell technology, shading, dirt and others that are not always measurable. PR can be calculated according to Equation 2 and is expressed as a percentage [7].

$$PR = \frac{YF}{\text{irradiation}/1000} \tag{2}$$

The Capacity Factor (FC) is a figure of merit that shows the amount of energy that can be generated if the system operates at its nominal power all the time. In Brazil, the FC for GCPVS averages between 13% to 18% [7]. The FC can be calculated according to Equation 3, and is expressed as a percentage.

$$FC = \frac{\text{energy generated}}{\text{nominal power} * \text{time}} \tag{3}$$

The generation data necessary for the calculation of Equations 1, 2 and 3 were obtained through the remote monitoring systems of GCPVS. The inverters of the systems are from different manufacturers (Fronius, ABB, Refusol and SMA). However, all of these have a monitoring system, where it is possible to check various system data online, both in real time and historical data, such as DC voltage, AC voltage, current, generation power, among others.

In this study, the monthly generation values of each system were used to calculate the figures of merit previously described. The monthly generation values for each of the systems refer to the period from August 2018 to July 2019 and can be seen in Table 1a and Table 1b. The blank cells in these tables mean that there are no monthly data available for the given GCPVS. These tables also show the installed power capacity in each system. In Cascavel it was 21.76 kWp, in Goioerê 25.67 kWp, in Rancho Alegre D’Oeste 6.03 kWp and in Ubiratã 3.35 kWp.

Table 1a. Monthly Generation – January to June (kWh).

City	Power (kWp)	Jan	Feb	Mar	Apr	May	Jun
Cascavel 1	3.52	418.73	410.76	351.13	475.48	391.91	257.59
Cascavel 2	18.24	2439.26	2028.99	1971.49	1644.08	1183.77	1135.79
Goioerê 1	7.92						739.12
Goioerê 2	6.03				672.46	559.82	590.10
Goioerê 3	3.685						369.79
Goioerê 4	8.04						
Rancho Alegre D'Oeste	6.03	889.36	735.87	806.31	652.92	535.55	574.18
Ubiratã	3.35						283.64

Table 1b. Monthly Generation – July to December (kWh).

City	Power (kWp)	Jul	Aug	Sep	Oct	Nov	Dec
Cascavel 1	3.52	328.03	395.43	369.6	319.27	389.47	390.2
Cascavel 2	18.24	1619.15	1818.49	1885.22	1762.32	2638.35	2951.09
Goioerê 1	7.92	731.08	933.3	875.58	957.58	988.99	1017.08
Goioerê 2	6.03	608.19	752.32	738.61	836.31	874.5	897.62
Goioerê 3	3.685	377.01	458.46	444.66	498.16	513.48	537.71
Goioerê 4	8.04	721.95	914.77	957.11	1099.32	1152.98	1189
Rancho Alegre D'Oeste	6.03	563.62	726.59	724.49	535.51	872.82	919.37
Ubiratã	3.35	294.53	373.01	389.91	458.87	456.85	460.18

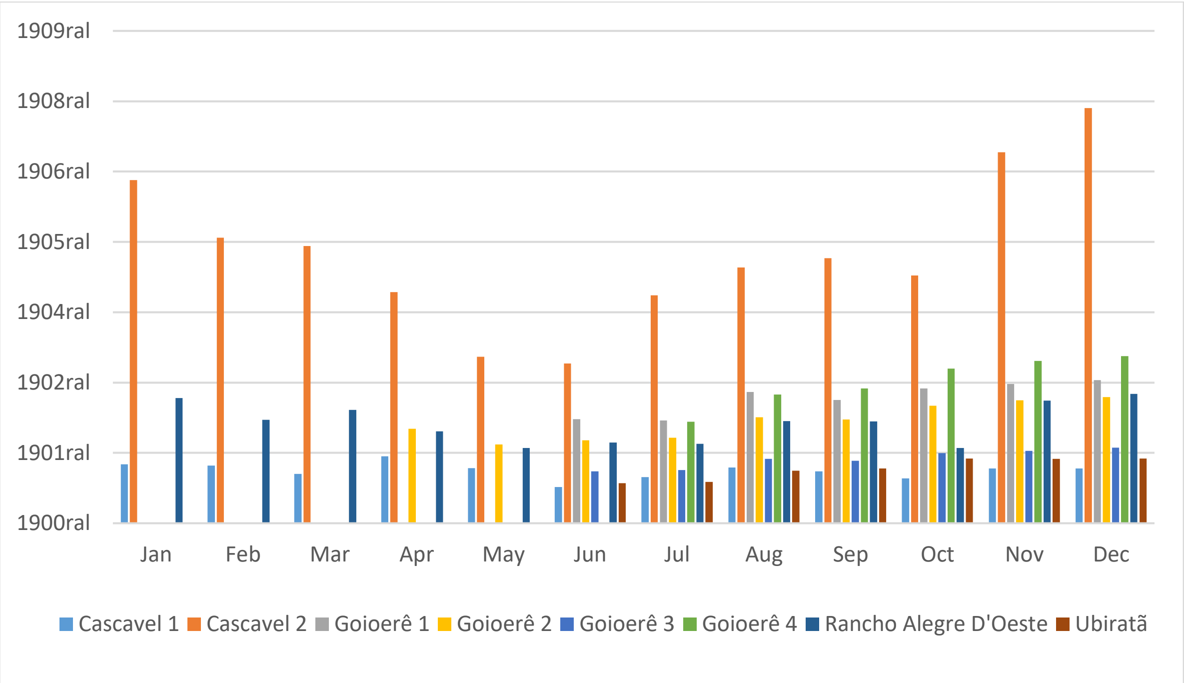

Figure 1. Electric energy generation (kWh)

To calculate the expected generation of each system, the PR value adopted was 75%, following the percentage adopted in the Solar Energy Atlas of the State of Paraná [8]. Thus, the inclined plane irradiation data and the expected yield values per kWp taken from the data available in the referent Atlas [8] are shown in Table 2 and Table 3, respectively.

Table 2. Irradiation on the inclined plane by city (kWh/m².day) [8].

City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cascavel	5.5	5.3	5.4	5.1	4.3	4.0	4.2	5.2	4.8	5.1	5.4	5.5
Goioerê	5.5	5.5	5.6	5.2	4.4	4.1	4.3	5.2	4.9	5.2	5.5	5.7
Rancho Alegre D'Oeste	5.5	5.5	5.5	5.2	4.4	4.1	4.3	5.2	4.9	5.2	5.6	5.6
Ubiratã	5.6	5.3	5.5	5.2	4.4	4.1	4.2	5.2	4.9	5.1	5.5	5.6

Table 3. Expectation of final yield by city (kWh/kWp) [8].

City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cascavel	128	111	125	114	99	90	97	120	107	118	122	128
Goioerê	128	115	128	117	103	92	100	120	110	122	125	131
Rancho Alegre D'Oeste	129	116	130	118	103	92	100	121	111	122	125	131
Ubiratã	131	111	129	117	103	91	98	120	110	119	124	131

RESULTS AND DISCUSSION

Before going into details on the comparison of the GCPVS, it is worth noting that, for the calculation of the figures of merit, the atmospheric data for the generation months were not considered, it was considered the average showed by the Solar Energy Atlas of the State of Paraná [8]. Also, no adjustments were made regarding the inclination and orientation of the systems. This strategy was chosen precisely to observe the behavior of PV panels in the most diverse and real cases situations, in comparison with the designed average values.

With the values shown in Table 1a and Table 1b, the final yield values (kWh/kWp) of the installed systems were calculated monthly, as shown in Table 4, and Figure 2.

Table 4. Final Yield (kWh/kWp).

City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cascavel 1	119	117	100	135	111	73	93	112	105	91	111	111
Cascavel 2	134	111	108	90	65	62	89	100	103	97	145	162
Goioerê 1						93	92	118	111	121	125	128
Goioerê 2				112	93	98	101	125	122	139	145	149
Goioerê 3						100	102	124	121	135	139	146
Goioerê 4							90	114	119	137	143	148
Rancho Alegre D'Oeste	147	122	134	108	89	95	93	120	120	89	145	152
Ubiratã						85	88	111	116	137	136	137

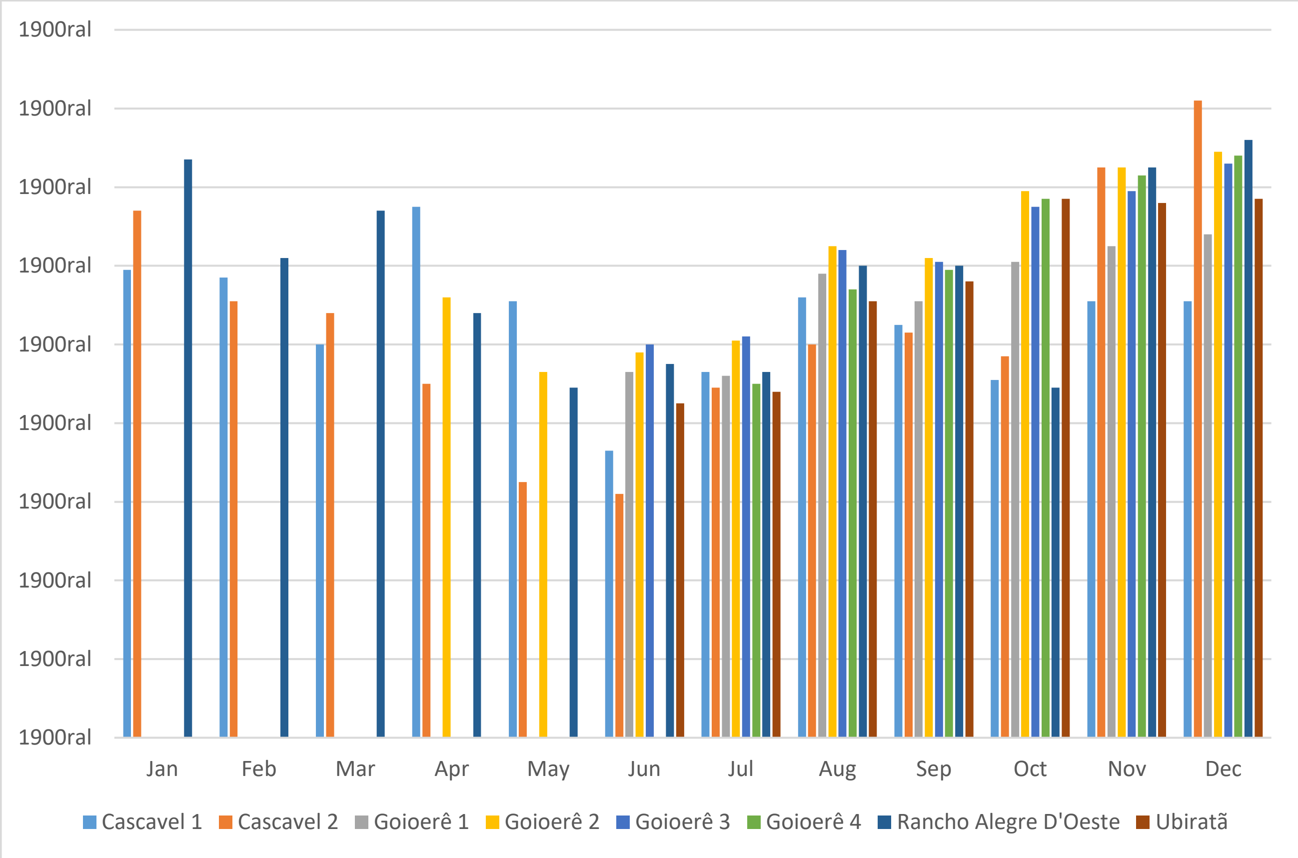

Figure 2. Final Yield (kWh/kWp)

Lower values were found, in average, in May, June and July. This behavior is expected in these months due to the lower radiation levels in these periods, leading to a smaller energy generation. The values for yield were higher during December and November, the average for these months were 136 kWh/kWp and 142 kWh/kWp, respectively, due to high levels of irradiance, leading to higher values of energy generation, thus increasing the yield of PV systems.

The highest annual average yield calculated was from the system Goioerê 4 (125.17 kWh/kWp), while the system with the lowest value was Cascavel 2 (105.5 kWh/kWp), and their percentual difference was 18.67%. Even though Goioerê 4 system did not present the highest monthly values in any month, it was installed in July, and then it did not have low values commonly found in winter months. The system Cascavel 2 had the highest monthly values in November and December, however, due to the fact that its values were the lowest in May and June (65 and 62 kWh/kWp), the system had a low value of the annual average. Besides that, the systems Goioerê 3 and Goioerê 2 had the second highest and the third-highest annual average values, with 123.86 kWp/kWh and 120.44 kWp/kWh, respectively. The percentual difference between them and the annual average value of Goioerê 4 were 3.77% from Goioerê 2 and 1.05% from Goioerê 3. The systems installed in Cascavel presented the lowest annual average values, which were close to each other, with a percentual difference of 0.94%.

The calculated yield values were compared with the expected yield values, according to the monthly irradiation data from the Solar Energy Atlas of the State of Paraná [8]. Table 5 presents the percentage value of the division of the generated value by the expected value. Thus, values above 100% means that the system generated more than expected for that month, similarly, values below 100% means that the generation was lower than expected.

Table 5. Comparative of productivities calculated and provided by the Solar Energy Atlas of the State of Paraná (%).

City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cascavel	93	105	80	118	112	81	96	94	98	77	91	87
Cascavel	104	100	86	79	66	69	92	83	97	82	119	126
Goioerê						101	92	98	101	99	100	98
Goioerê				95	90	106	101	104	111	114	116	114
Goioerê						109	102	104	110	111	111	111
Goioerê							90	95	108	112	115	113
Rancho Alegre D'Oeste	114	105	103	92	86	104	93	100	108	73	116	116
Ubiratã						93	90	93	106	115	110	105

Large variations in Table 5 are expected, as the values of the figures of merit are not being adjusted according to their positioning, nor are the actual monthly irradiation values of the periods being used. However, it is noted by the average of the comparison that these tend to converge to 100%. In other words, the annual generation values tend to approximate the expected annual generation value, as the annual comparison minimizes the effects of months that have atypical irradiation values and the differences generated by non-ideal positioning of GCPVS.

Like the calculation performed for the Final Yield, Table 6 presents the monthly PR values for each system. The Figure 3 represents the PR of the studied systems.

Table 6. Performance Ratio (PR) (%).

City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cascavel 1	69.9	78.9	59.8	89.0	84.1	61.3	71.7	70.1	73.2	57.7	68.3	65.0
Cascavel 2	78.6	75.2	64.8	59.4	49.0	52.2	68.3	62.2	72.1	61.5	89.3	94.9
Goioerê 1						76.2	69.6	73.4	74.9	74.4	75.1	73.3
Goioerê 2				71.2	67.5	80.0	76.0	77.7	83.0	85.4	87.3	85.0
Goioerê 3						82.0	77.1	77.5	81.8	83.2	83.8	83.3
Goioerê 4							67.7	70.9	80.7	84.2	86.3	84.4
Rancho Alegre D'Oeste	86.2	79.4	78.1	69.1	64.7	77.6	70.1	75.3	81.7	54.8	86.9	87.5
Ubiratã						69.5	67.0	69.6	79.2	86.3	82.5	78.8

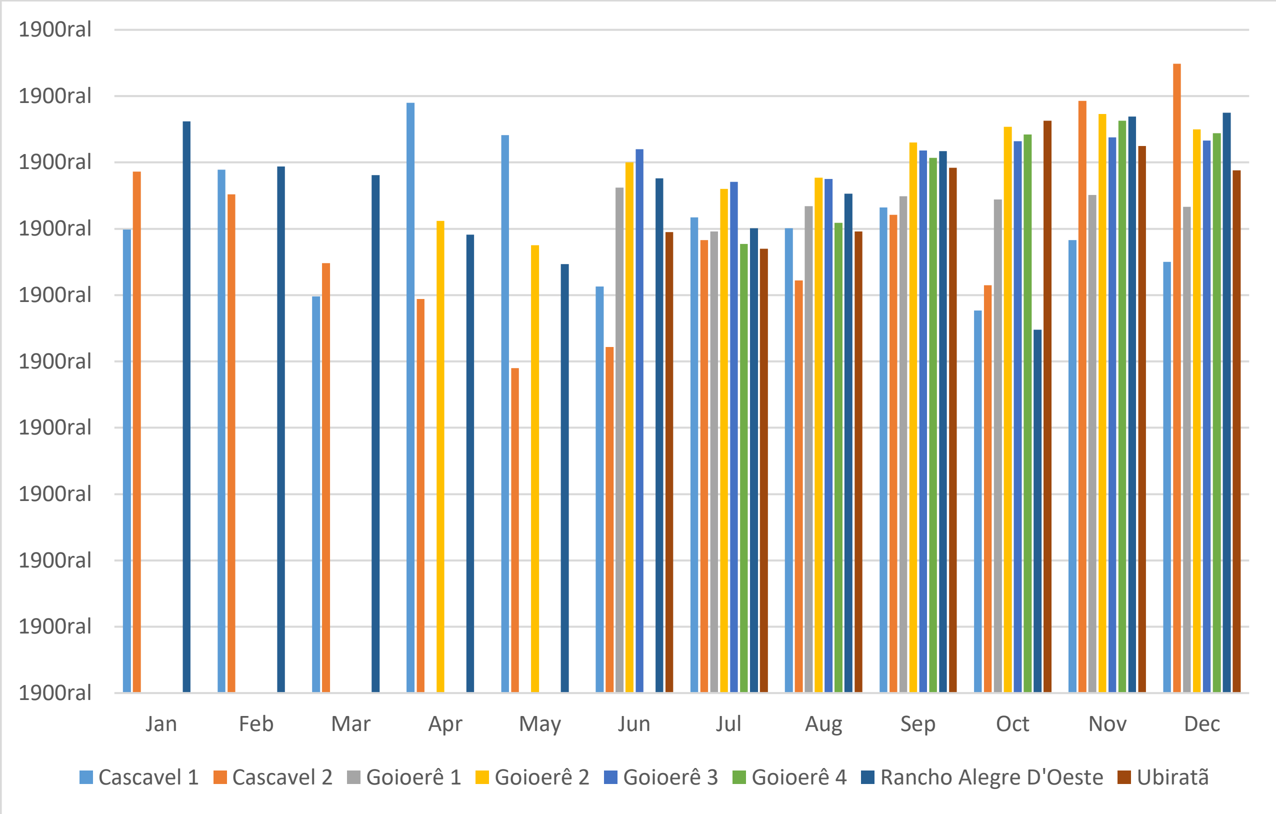

Figure 3. Performance ratio (%)

The lowest PR are found in the winter months, as it is a period of lower energy generation, while the highest values are in the summer months. In winter the average PR was 70%, and in summer this value reached 80%, on average. PRs that were close to 50% occurred either due to system shutdowns for a few days during that months, of for a higher effect of shading on the systems.

The system Goioerê 3 presented the highest annual average PR value (81.24%), while the system Cascavel 2 had the lowest (68.96%). Besides that, the systems Goioerê 2, 3, and 4 presented the highest annual average PR values and the systems Cascavel 1 and 2 had the lowest. About the system of Rancho Alegre D'Oeste, the monthly values of January, February and March were the highest in comparison with the other systems and this system had the fifth-highest annual average value (75.95%), with a percentual difference to the system Goioerê 3 of 6.51%. The system Ubiratã had the fourth-highest annual PR average value (76.13%), with a percentual difference to the system Goioerê 3 of 6.30%.

Table 7 shows the comparison of the values obtained in Table 6 with the expected PR (in this case the value of 75% was used for all months), presented by the Solar Energy Atlas of the State of Paraná [8].

Table 7. Comparison of Calculated Values of Performance Ratio (PR) and Values presented by the Solar Energy Atlas of the State of Paraná (%).

City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cascavel 1	93	105	80	119	112	82	96	93	98	77	91	87
Cascavel 2	105	100	86	79	65	70	91	83	96	82	119	127
Goioerê 1						102	93	98	100	99	100	98
Goioerê 2				95	90	107	101	104	111	114	116	113
Goioerê 3						109	103	103	109	111	112	111
Goioerê 4							90	94	108	112	115	113
Rancho Alegre D'Oeste	115	106	104	92	86	103	93	100	109	73	116	117
Ubiratã						93	89	93	106	115	110	105

Again, as expected, the monthly variations are greater than the average annual variations. In fact, when considering the average of the annual averages of the PR of all systems, the value of 72.4% is obtained, very close to the 75% considered by the Solar Energy Atlas of the State of Paraná [8]. This percentage difference may be linked to the fact that the installed systems are not in ideal conditions, however, they are being calculated as if they were, without making the necessary adjustments in irradiation according to the inclination and orientation of each system.

To complete the performance analysis, the third figure of merit was calculated: the capacity factor. It is shown in Table 8 and Figure 4, with monthly values of FC for each of the systems.

Table 8. Capacity Factor (FC) (%).

City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cascavel 1	16.0	17.4	13.4	18.8	15.0	10.2	12.5	15.1	14.6	12.2	15.4	14.9
Cascavel 2	18.0	16.6	14.5	12.5	8.7	8.6	11.9	13.4	14.4	13.0	20.1	21.7
Goioerê 1						13.0	12.4	15.8	15.4	16.3	17.3	17.3
Goioerê 2				15.5	12.5	13.6	13.6	16.8	17.0	18.6	20.1	20.0
Goioerê 3						13.9	13.8	16.7	16.8	18.2	19.4	19.6
Goioerê 4							12.1	15.3	16.5	18.4	19.9	19.9
Rancho Alegre D'Oeste	19.8	18.2	18.0	15.0	11.9	13.2	12.6	16.2	16.7	11.9	20.1	20.5
Ubiratã						11.8	11.8	15.0	16.2	18.4	18.9	18.5

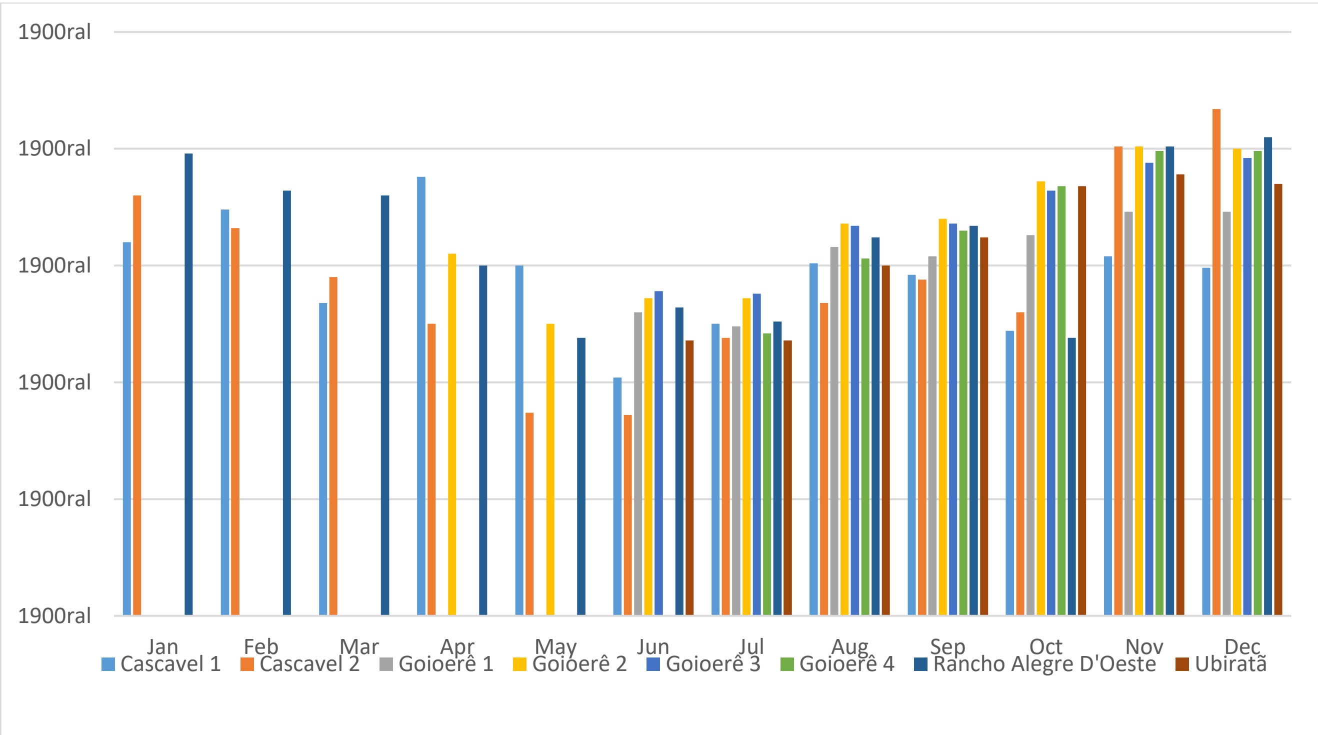

Figure 4. Capacity Factor (%).

The capacity factors of the eight systems fluctuate within expectations for installations in Brazil. Values greater than 18% are more recurrent in summer months, which have higher levels of irradiation, while capacity factors below 13% occur in winter months, when irradiation is lower.

According to Silveira and coauthors [9], the average capacity factor for six years of operation of a photovoltaic system resulted in 12.85%, while a two-year photovoltaic system presented a percentage of 13.97%. Both systems are installed in Curitiba, capital of Paraná. In a monthly analysis, the behavior of these systems was also influenced by climatic variation throughout the year, ranging from 9% in winter months to 19% in summer months.

The systems installed in the city of Cascavel had the lowest FC values in most months of the year, with the exception of the months of July and October. During six months, Cascavel 2 system presented the lowest monthly FC values. On the other hand, Cascavel 4 system presented lower monthly FC values in four.

In a general analysis, it can be concluded that the indexes presented in this article are adequate within this perspective of other systems in the same state.

CONCLUSION

The yield and performance ratio values had the same behavior: higher values in summer and lower in winter. This is due to the fact that summer presents higher irradiation value, when compared to winter, and, consequently, the PV panels generate more energy in this season.

Besides, the values of performance ratio higher than 90% can be explained by the fact that the irradiation used as the reference to the calculus was not provided by solarimetric stations, although it was provided by the data of the Solar Energy Atlas of the State of Paraná. For being a 17-year-old study, the referred Atlas presents a historical average and does not consider the particularities of the meteorological conditions that could have happened during the year of the studied cases.

In relation to the comparative analysis of the yield of the systems of different cities, Goioerê presented the lowest difference between the calculated values and the data from Solar Energy Atlas of the State of Paraná, while Cascavel presented the highest.

In addition, the Goioerê system 4 presented the highest annual average value of yield and capacity factor value compared to the other systems analyzed. Besides that, Goioerê 3 system presented highest annual average value of Performance Ratio than the other systems. The Cascavel 2 system presented the lowest annual average values of final yield, performance ratio and capacity factor when compared to the others.

In general, the values presented by the systems studied were fairly close to their expected values, validating both the data presented in Solar Energy Atlas of the State of Paraná, and the correct installation of the systems in question. This confirms that, as long as the system is installed correctly, and on situations as close as possible to the ideal conditions, the calculation of the expect energy generation, as long as done correctly and using a valid databank, is a valid tool.

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