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A N I N T E R N A T I O N A L J O U R N A L

Analysis of the Operation of Photovoltaic Systems Installed at Federal University of Technology - Paraná in Curitiba

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ABSTRACT

The Federal University of Technology - Paraná (UTFPR), Campus Curitiba, has a Grid-Connected Photovoltaic System (GCPVS) of 2.1 kWp in the Green Office (GO), which has been in operation since December 2011, and until September 2017 generated little more than 13.64 MWh and a GCPVS of 10.2 kWp, in operation since February 2016. The photovoltaic panel of the 2.1 kWp system was set up following the inclination of the roof of the building, which does not give its maximum performance. On the other hand, the panel of the 10.2 kWp system in Neoville was installed in optimum conditions, that is, oriented to the north and with slope equal to the latitude of Curitiba and, up tol September 2017 generated more than 20.65 MWh. This paper presents the monitoring of the electric energy generated by the systems and also a history of the merit indexes of the GCPVS, which are: Productivity (Yield); Performance Ratio; and Capacity Factor. These indexes allow to evaluate the performance of the GCPVS and make a comparison between them. Finally, the photovoltaic generation of both GCPVS proved to be a sustainable and effective form of distributed generation of electric energy in the urban environment.

Keywords: solar energy, distribuited generation, grid-connected photovoltaic system

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INTRODUCTION

The grid-connected photovoltaic system shows great growth among renewable energy sources worldwide with 75GW installed in 2016, which corresponds to the installation of more than 31.000 photovoltaic modules per hour. In addition, more photovoltaic capacity was installed in 2016 than the global photovoltaic capacity accumulated in the five previous years. The year of 2016 recorded a total photovoltaic capacity of 303GW, while the year of 2015 achieved 228 GW (48% less than 2016), 2014 added 177GW installed (71% below 2016) and 2013 accumulated 137 GW (220% below 2016)[1].

A grid-connected photovoltaic system is basically composed of a Photovoltaic (PV) panel, which converts the energy of the sun into electrical energy in direct current, and an inverter, which converts the direct current into alternating current, with voltage and frequency compatible with the utility grid to which the system is interconnected. The main advantages of this type of system are: high productivity, absence of bank of batteries and automatic shutdown in case of lack of power of the network, avoiding the phenomenon of islanding[2].

In December 2011, the Green Office (GO) of the Federal University of Technology - Paraná (UTFPR) was inaugurated, a unique proposal in Brazil for a sustainable building of 150 m^2 that adopted several sustainability strategies in partnership with more than sixty companies, aiming to verify the performance of these strategies, among them, the maximum energy efficiency[3]. In addition to taking advantage of natural lighting and the use of LED lamps, the project also opted for the photovoltaic generation technique as a master line to provide energy to the building, together with the utility's electrical system. Figure 1 shows the Green Office of the UTFPR.

Figure 1 – UTFPR`s Green Office

In February 2016, a GCPVS was installed at the Neoville (another campus of UTFPR in Curitiba), which was donated by the company ELCO Engenharia. This photovoltaic system has a total installed power of 10.2 kWp, consisting of 2 sets of 17 photovoltaic modules connected in series, and the inverter used in the system has a nominal output power of 10 kW[4]. Figure 2 shows the view of this system.


Figure 2 - Neoville's System

Both systems are based on the interaction of two agents responsible for the supply of electric energy: the energy distribution company and the photovoltaic generator. When there is solar incidence on the photovoltaic panel, there is generation of electric energy, and this is made available directly in the electricity grid of the consumer where the photovoltaic generator is located. In case the photogenerated energy is higher than the consumed, it is sent to the electricity grid to be consumed in the neighborhood. In moments of low or no solar incidence, the distributor supplies the consumer[5].

MATERIAL AND METHODS

A. Work place - data collected directly from the grid-connected photovoltaic system of UTFPR installed in the city of Curitiba.
B. Procedure - With the irradiation data provided by the pyranometer, the National Institute of Meteorology (INMET)[6], for the A807 station located in Curitiba and, with the aid of the RADIASOL program, provided by the Federal University of Rio Grande do Sul[7]. With this program it is possible to determine irradiation that effectively affects the photovoltaic panel of each system, since the input data of that program are the irradiation data in the horizontal plane and the output data are the irradiance values in the GCPVS plane (according to the respective slope and azimuthal deviation).
C. Data Analysis - Calculations of the merit indices of the systems were performed, using the universal equations for Productivity, Performance Rate and Capacity Factor [8,9,10].

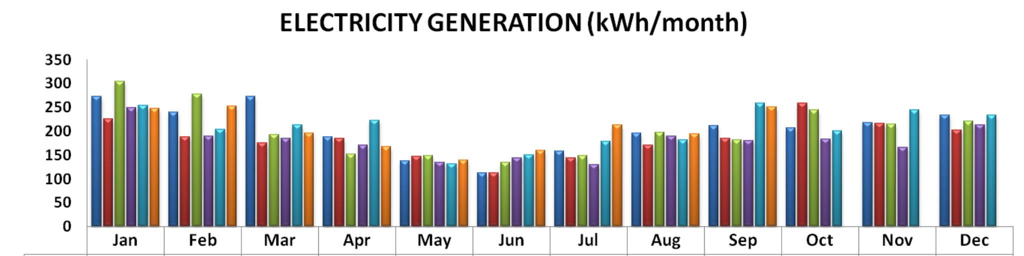
RESULT AND DISCUSSION

The analysis of the performance of these grid-connected photovoltaic system is based on the energy values generated during the entire period of operation and on the irradiance values incident on the PV panels. Based on the generated energy and incident radiation, the merit indexes of the GCPVS are studied, which are: yield; performance ratio and capacity factor.

Generated Energy

Analyzing the operation of the Green Office's system from 2012 to September 2017, a total generation of 13.64 MWh was observed in this period. The generation of electric energy is proportional to the irradiation incident in the PV panel, where in the summer months (higher solar incidence) there is a larger generation of electric energy and in the winter months, (lower solar incidence) there is less generation. Figure 3 shows the electric energy values generated in each month of Green Office's system operation.

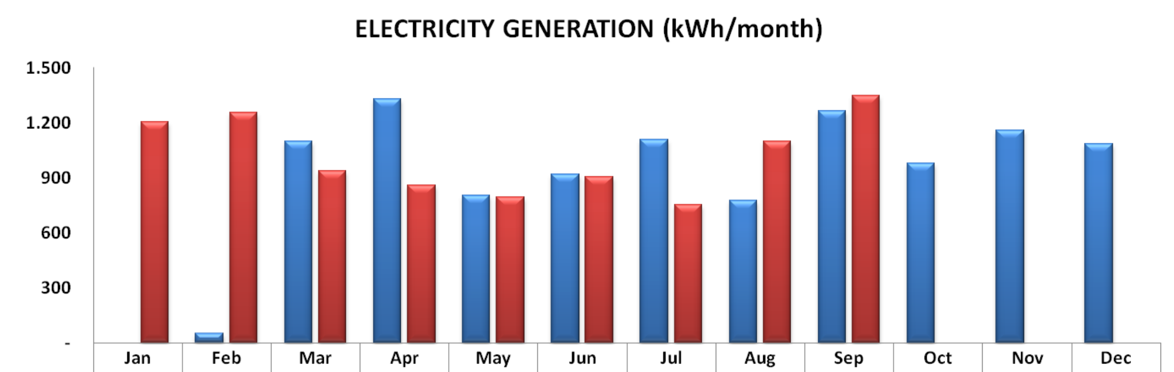
Table 3 - Electricity Generation (kWh /month) of Green Office



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2012	273	240	272	187	137	112	158	196	211	206	218	234
2013	225	188	175	185	147	112	144	170	184	258	216	202
2014	304	278	193	151	149	134	148	197	181	244	215	221
2015	249	190	184	170	135	144	130	189	180	183	165	213
2016	254	203	213	223	131	150	179	181	258	201	244	234
2017	248	252	195	168	139	160	213	194	250	-	-	-

Table 4 shows the electric power generation of Neoville's system. Since in operation, it has generated more than 20.65 MWh.

Table 4 - Electricity Generation (kWh /month) of Neoville's System



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2016	-	50,3	1100,8	1329,3	802,3	919	1106,2	775,5	1263,6	979,2	1158,4	1082,7
2017	1203,8	1254,7	937,1	856,8	792,9	905,2	753,1	1096,3	1347,3	-	-	-

Photovoltaic Panel Incident Irradiation

The irradiance values of the photovoltaic panels, which served as the basis for the calculation of some of the merit indexes of the PV system, were obtained from the National Institute of Meteorology (INMET) database for station A807, located in the metropolitan area of Curitiba[6].

As the INMET pyranometer is installed horizontally, the RADIASOL program is used to determine the irradiation that effectively affects the panel of each system. In the case of Green Office, the slope of the panel is 15º and the azimuthal deviation of 22º west, while the Neoville's panel is inclined 25º and the azimuthal deviation is zero.

This program, provided by the Federal University of Rio Grande do Sul[7], allows the identification of irradiance values for any plane (different slopes and azimuthal deviation from the north) from the insertion of the irradiation values in the horizontal plane.

For the period of 2012 to 2017 the stations - EV_UTFPR_2012, EV_UTFPR_2013, EV_UTFPR_2014, EV_UTFPR_2015, EV_UTFPR_2016 and EV_UTFPR_2017 - were created in the RADIASOL program of UFRGS. Figure 5 shows the EV_UTFPR_2016 screen, in which the irradiance values for the year 2016 were edited in the horizontal plane for the geographic position (-25.440418, -49.268610) where the PV photovoltaic panel is installed and then the slope and azimuthal deviation values were adjusted, thus obtaining the graph shown in Figure 5 with the irradiation values incident on the plane of the photovoltaic panel. Similarly, this same procedure was performed to obtain the irradiation values incident on the Neoville panel.

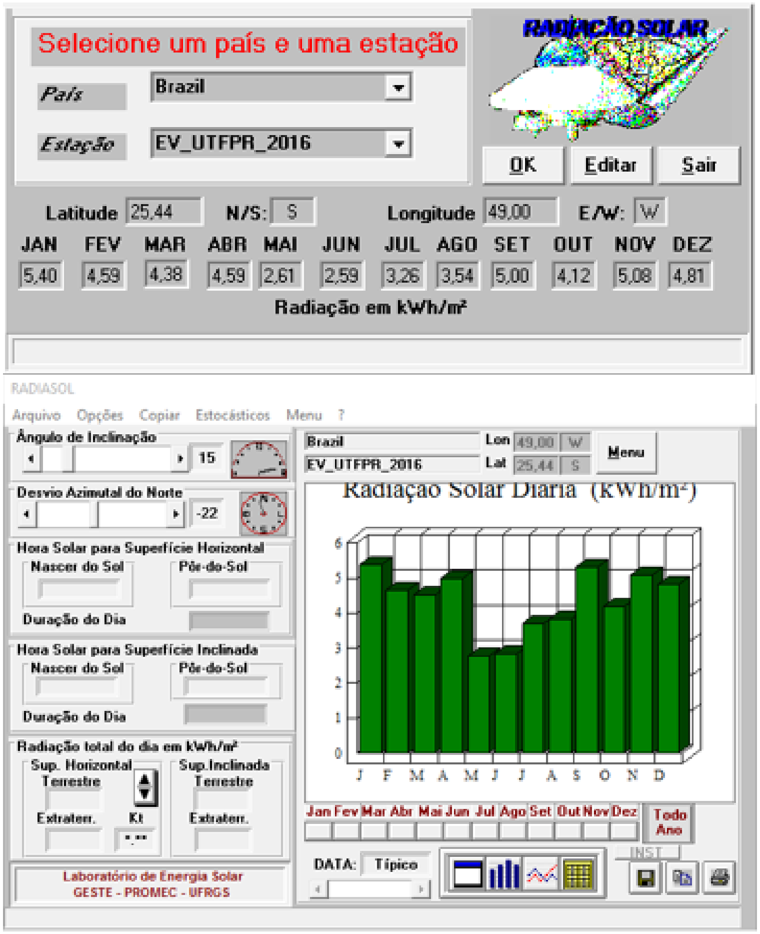


Figura 5 - Radiasol screen

Merit indexes

The merit indexes are used to compare the operation of PV systems located at different locations and with different nominal powers[8,9,10].

Yield

It is the relation between the generated power (kWh) and the installed PV power (kWp), usually linked to a year of operation, annual yield, but it can also be considered the monthly yield. Equation 1 shows the quantity in question. Table 1 shows the monthly and annual yield of the two grid-connected photovoltaic systems.

$$Y = \frac{Generated_{energy}}{PV_{power}} \frac{[kWh]}{[kWp]} \quad (1)$$

Table 1 - Annual and monthly yield of the UTFPR's grid-connected photovoltaic systems
Values calculated applying the equation above

YIELD (kWh/kWp)								
Month	GO						Neoville	
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2016**	**2017**
Jan	130	107.14	144.76	118.57	120.95	118.1	--	118.02
Feb	114.29	89.52	132.38	90.48	96.67	120	--	123.01
Mar	129.52	83.33	91.9	87.62	101.43	92.86	107.92	91.87
Abr	89.05	88.1	71.9	80.95	106.19	80	130.32	84
May	65.24	70	70.95	64.29	62.38	66.19	78.66	77.74
Jun	53.33	53.33	63.81	68.57	71.43	76.19	90.1	88.75
Jul	75.24	68.57	70.48	61.9	85.24	101.428571	108.45	73.8333333
Aug	93.33	80.95	93.81	90	86.19	92.3809524	76.03	107.480392
Sep	100.48	87.62	86.19	85.71	122.86	119.047619	123.88	132.088235
Oct	98.1	122.86	116.19	87.14	95.71		96	
Nov	103.81	102.86	102.38	78.57	116.19		113.57	
Dec	111.43	96.19	105.24	101.43	111.43		106.15	
Year	**1,163.81**	**1,050.48**	**1,150.00**	**1,015.24**	**1,176.67**	**553.33**	**1,243.21**	**583.38**

It is noted that the productivity value, which is a result of the ratio of the generated energy divided by the installed photovoltaic power, presented close results during the entire period of operation of the GCPVS of the GO. It is evident that accumulation of dirt directly affects the productivity of the system, since after the cleanups, carried out on 8/31/2013, 9/26/2015 and 9/1/2016, productivity rises again.

On the other hand, Neoville's grid-connected photovoltaic system results show greater productivity from March to July.

Performance Ratio

It is the relationship between productivity (kWh / kWp) and the hours of sunshine hours at 1,000W/m² incident on the PV panel, also usually linked to a year of operation, annual performance ratio, but also the monthly performance ratio. This quantity is expressed as a percentage, Equation 2 presents the magnitude in question, and Table 2 presents the Performance Ratio of the grid-connected photovoltaic system.

$$PR = \frac{Yield}{Irradiation / 1{,}000}[\%] \quad (2)$$

Table 2 - Monthly and annual performance ratio of the UTFPR's grid-connected photovoltaic systems
Values calculated applying the equation above

PERFORMANCE RATIO (%)								
Month	**GO**						**Neoville**	
	2012	2013	2014	2015	2016	2017	2016	2017
Jan	74.59%	67.54%	76.74%	64.41%	72.52%	73.54%	--	73.64%
Feb	74.89%	67.58%	87.99%	66.35%	71.99%	74.93%	--	77.89%
Mar	75.46%	69.12%	65.94%	68.39%	72.39%	74.33%	75.03%	73.54%
Abr	74.32%	65.74%	73.01%	68.59%	71.08%	75.33%	83.70%	77.56%
May	70.52%	67.57%	71.15%	69.22%	72.65%	72.63%	88.72%	82.49%
Jun	77.29%	68.53%	74.68%	69.01%	83.54%	78.14%	97.83%	85.50%
Jul	78.62%	67.64%	79.77%	59.08%	74.72%	95.39%	75.40%	56.57%
Aug	63.40%	65.88%	65.47%	61.13%	72.97%	83.47%	60.56%	93.96%
Sep	68.11%	75.84%	62.20%	66.91%	77.12%	77.50%	71.44%	84.19%
Oct	66.13%	75.92%	62.57%	74.43%	73.69%		74.26%	
Nov	66.24%	70.93%	64.72%	62.66%	76.24%		75.71%	
Dec	66.33%	56.26%	64.55%	65.05%	74.73%		72.85%	
Year	**71.33%**	**68.21%**	**70.73%**	**66.27%**	**74.49%**	**74.82%**	**77.55%**	**77.02%**

Analyzing the months immediately prior to the GO PV panel cleanings, a gradual decrease was observed in this index, and after the cleanings, the monthly performance rate returned to the level observed in the first months of operation of the GCPVS, remaining higher than 70%.
Neoville has already performance rates above 71% in every month. It is interesting to note that the Neoville's performance rate for the year 2016 was 4% higher than the GO for that year.

Capacity Factor

It is its real capacity to generate energy according to the energy it would generate if operated at nominal power for 24 hours a day, also expressed as a percentage[8]. Equation 3 presents the magnitude in question, and Table 3 shows the Capacity Factor for 2012, 2013, 2014, 2015, 2016 and until September 2017 for the GCPVS of the GO's grid-connected photovoltaic system. This greatness is also shown for the Neoville's grid-connected system for 2016 and until September 2017.

$$CF = \frac{Generated_{energy}}{PV_{power} \times 24 \times days}[\%] \quad (3)$$

Table 3 - Monthly and annual capacity factor of the UTFPR's grid-connected photovoltaic systems
Values calculated applying the equation above

CAPACITY FACTOR (%)								
Month	**GO**						**Neoville**	
	2012	2013	2014	2015	2016	2017	2016	2017
Jan	17.47%	14.40%	19.46%	15.94%	16.26%	15.87%	--	15.86%
Feb	16.42%	13.32%	19.70%	13.46%	13.89%	17.86%	--	18.31%
Mar	17.41%	11.20%	12.35%	11.78%	13.63%	12.48%	14.51%	12.35%
Abr	12.37%	12.24%	9.99%	11.24%	14.75%	11.11%	18.10%	11.67%
May	8.77%	9.41%	9.54%	8.64%	8.38%	8.90%	10.57%	10.45%
Jun	7.41%	7.41%	8.86%	9.52%	9.92%	10.58%	12.51%	12.33%
Jul	10.11%	9.22%	9.47%	8.32%	11.46%	13.63%	14.58%	9.92%
Aug	12.54%	10.88%	12.61%	12.10%	11.58%	12.42%	10.22%	14.45%
Sep	13.96%	12.17%	11.97%	11.90%	17.06%	16.53%	17.21%	18.35%
Oct	13.18%	16.51%	15.62%	11.71%	12.86%	--	12.90%	--
Nov	14.42%	14.29%	14.22%	10.91%	16.14%	--	15.77%	--
Dec	14.98%	12.93%	14.14%	13.63%	14.98%	--	14.27%	--
Year	**13.25%**	**12.00%**	**13.16%**	**11.60%**	**13.41%**	**12.80%**	**14.06%**	**13.49%**

The average Capacity Factor of the GO in 2015 was lower than the other years, due to the lower solar irradiation in that year. Neoville's average capacity factor for 2016 was 5% higher than the GO value.

CONCLUSION

The monitoring of the GO and Neoville's grid-connected systems in Curitiba for the analyzed period confirm the urban applicability of distributed photovoltaic generation. Thus, these PV systems operate in a clean, silent and that does not require additional area to be installed, since the photovoltaic panels are installed on the roofs of the buildings. Both grid-connected photovoltaic systems are shown as high reliability systems, since they operate uninterruptedly from the respective installations. It is important to highlight that these PV systems had no replacement of equipment, and cleaning of the photovoltaic modules is the only intervention that has been performed.

Regarding merit indexes: Yield, Performance Ratio and Capacity Factor, the values are adequate and similar to those published by other universities that conduct research in this field, such as UFSC and USP. The irradiance values considered for the calculation of the Performance Ratio were obtained through the meteorological station of INMET (A807). This station has a pyranometer installed horizontally, providing the values of irradiation in the horizontal plane, with the use of the RADIASOL program, irradiation was obtained in the plane of the PV panel of GO and Neoville.

After five years and nine months of operation of the GO, an average generation of 2.25MWh/year was observed; Average annual Yield of 1.070kWh / kWp; Average Performance Ratio of 71.57% and Average Capacity Factor greater than 12.78%, which are regular indexes for this type of installation. As. for the first year and six months of operation of the Neoville there is an average generation of 9.86 MWh/year; Average annual Yield of 966.4kWh / kWp; Average Performance Ratio of 78.05% and Average Capacity Factor greater than 13.90%. It is noted that the Neoville's grid-connected photovoltaic system presented higher results than the GO.

However. it is important to mention that the 10.2 kWp Neoville's grid-connected photovoltaic system uses a 380V three-phase transformerless of the high efficiency with maximum efficiency of 98%, while the GO's grid-connected photovoltaic system of the 2.1 kWp employs a single-phase inverter with a low-frequency transformer and maximum efficiency of 92%. The non-transformer inverter has less losses than the inverter with transformer and for this reason, it is superior to the other. In addition, these inverters are lighter, more compact and use components with more technology than inverters with transformer. This is the main trend of the photovoltaic market regarding inverters, that is, to use non-transformer inverters in order to increase the system's efficiency.

In addition, the Neoville's photovoltaic panel system was installed in optimum conditions, that is, geographically oriented north and with tilt angle equal to the latitude of Curitiba (25º) - without azimuthal deviation. On the other hand, the GO's photovoltaic panel was installed alongside the inclination and orientation of the respective roofs. Furthermore, the GO' system panel is very closely attached to the roof, which reduces the ventilation of the panel and thereby causes the modules to heat up more than the modules of the other GCPVSs that have greater ventilation and consequently reduces its productivity.

Finally, it is noticed that the choice of the inverter and the way of installation of the photovoltaic modules are determinant factors to maximize the performance of the photovoltaic system. For this reason, this type of equipment and its installation must be carefully chosen during the design phase of the system.

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