Photovoltaic Distributed Generation Connecting to the Grid: Analysis of Solar Incident Irradiation and Electricity Generation in the Federal University of Ceara

Douglas A. C. Costa[1], Paulo C. M. Carvalho[2], Bruno F. Menezes, Francisco J. R. Silva[3], Obed L. Vieira[2], Fellipe S. Soares[2] and Pollyana R. Carvalho[2]

[1] Federal Institute of Education, Science and Technology of Ceara (IFCE), Cedro, Ceara (Brasil)

[2] Federal University of Ceara (UFC), Fortaleza, Ceara (Brasil)

[3] UniFanor Wyden University Center (UNIFANOR), Fortaleza, Ceara (Brasil)

[3] University Center September 7 (UNI7), Fortaleza, Ceara (Brasil)

Abstract

This article presents an analysis, in August 2017, about the characteristics of solar incident irradiation and the electricity generation from a photovoltaic (PV) distributed generation (DG), installed in the Laboratory of Alternative Energies (LEA) and connected to the grid of Pici Campus/UFC, Fortaleza/CE, Brasil. Data collection of solar irradiation and the electricity generation from the PV DG occurred in August 2017 through an acquisition system; the data are analyzed through the monthly average daily generation ($G_{mês}$), monthly average global irradiation ($Ig_{mês}$), average capacity factor PV (FC_{med}), efficiency of the PV DG (e_{FV}), standard monthly sample standard deviation (s_m) and the Pearson coefficient of variation (CVP_m). A $Ig_{mês}$ of 6.04 kWh/m², within a little dispersed band, with CVP_{m_ig} of 0.0810. A $G_{mês}$ of 8.65 kWh, with FC_{med} of 24.04%, in a low dispersion band, with CVP_{m_G} of 0.0736, thus reflecting in the electricity generation the high values irradiation of the region in which the study was performed. The average e_{FV} of the period under study was 14.71%, showing, also, that a high irradiation does not mean that the PV DG will have a high e_{FV}.

Keywords: **D**istributed Generation, Solar Energy, Photovoltaic Generation, Capacity Factor, Solar Irradiation.

1. Introduction

The electric power generation in Brazil is predominantly renewable, with renewable sources participated with 81.7% and hydraulic generation accounts for 68.1% of the Brazilian electric energy matrix in 2016 (EPE, 2017). The electricity rationing program in 2001 due to the lack of rainfall, which caused a critical state in the hydroelectric reservoirs, led the country to increase the participation of alternative sources of energy. Noting that in Brazil, although the hydraulic source is renewable, this is not an alternative source, since it is the main source of Brazilian electricity.

The need for new electric energy sources means that the regional potential is taken advantage of shaping changes in the generation model, which tend to seek the decentralization and diversification of the Brazilian electric energy matrix. The economic incentives, cost reduction and rapid technological development allow the use of photovoltaic (PV) plants connected to the electricity grid in a simple, efficient and profitable way (Lima, Ferreira and Morais, 2017).

On the other hand, there are some technical disadvantages, especially in relation to the questionable capacity of the current electrical networks. One of the main concerns with PV generation is intermittence, where electricity production is concentrated within a limited fraction of the time. In general, these hours do not correspond to peaks in the characteristic demand of daytime activity cycles, especially in urban systems. In this way, the electricity generation from PV generation may not be effective in responding to peaks in demand (Piano and Mayumi, 2017).

doi:10.18086/swc.2019.19.03 Available at http://proceedings.ises.org

In recent years Latin America has experienced a high devaluation of the regional currencies, causing inflation and, thus, increases in electricity tariffs in these countries, so the PV systems have accelerated investment parity (Cadavid and Franco, 2017).

In the same way the investment parit can be accelerated with a good average daily global irradiance, which in Brazil varies from 12 MJ/m² (3.33 kWh/m²) to regions located in the South and Southeast of the country up to 20 MJ/m² (5.55 kWh/m²) in the Northeast (Cresesb, 2000). Brazil has extremely favorable solar irradiation conditions, but PV generation plays a small role in the country (Shimura et al., 2016). The state of Ceara (Ce) has one of the highest solar incidence rates in the Brazilian territory, making it eligible to receive investments for the installation of solar PV plants.

In 2011, the first PV plants, resulting from the Public Call ANEEL13/2011, Strategic Project: "Technical and Commercial Arrangements for the Insertion of Solar Photovoltaic Generation in the Brazilian Energy Matrix" (ANEEL, 2011) begin the operation phase and promote the knowledge about the dynamics of installation of PV plants (Barbosa et al., 2014).

The PV generation in Brazil in 2016 was 85 GWh, although this year it represented only 0.01% of the country's domestic electric power generation supply (EPE, 2017), this generation has been increasing significantly since 2012, when Normative Resolution No. 482/2012 was issued, which provided the bases and conditions for the use of PV distributed generation (DG), which caused an increase in PV generation of 42,500% in 2016 compared to 2012. For a more recent comparison it can be stated that increased by 44.07% in 2016 when compared to 2015 (EPE, 2017).

Normative Resolution nº 482/2012 created in Brazil a credit compensation system (ANEEL, 2012), in which the PV DG installed in a residence can access the distribution network and supply the electricity needs of this residence, totally or partially, through the energy compensation system, boosting the installation and dissemination of PV DG throughout the country. PV DG stands out in relation to other renewable sources because it can be quickly installed in shops and residences, as well as being a quiet and clean electricity source that occupies idle places, characteristics that make it the best choice for the urban environment.

The year 2016 was marked as the year in which the electricity produced by the solar source was cheaper than the energy produced by the wind power source. In 2016, the world's smallest solar energy supply contract was signed with U $ 2.44 cents/kWh (Global Market Outlook, 2017).

Social perspectives can avoid conflict barriers for the introduction of PV DG on a scale of public utility and suggest socially acceptable solutions for technical and economic issues (Frate and Brannstrom, 2017).

Lima, Ferreira, and Morais (2017) analyzed the performance of a 2.2 kWp PV system installed at the State University of Ceara, Fortaleza, Brazil. The system was monitored from June 2013 to May 2014, with efficiency of all panels, inverter and PV DG of 13.3%, 94.6% and 12.6%, respectively. The annual capacity factor of PV DG was 19.2%.

Costa et. al. (2017) presented a study about characteristics of a PV DG installed in the urban area of Fortaleza/Ce, Brazil. The data collection of this PV DG is carried out from July to December 2016. The capacity factor in the period studied reached a maximum value of 25.63% in September and a minimum value of 20.13% in December, showing a great generation potential.

This article presents an analysis, in August 2017, about the characteristics of solar incident irradiation and the electricity generation from a photovoltaic PV DG connected to the grid of Pici Campus, Fortaleza/CE, Brasil. In the present study allowed us to draw a panorama of the generation of a PV DG in the month of August 2017 for the city of Fortaleza.

2. Mathematical Formulation

2.1. Monthly average daily generation

The average monthly generation in month m ($G_{mth\,m}$) is the average of daily generations of all days that presented measurements, according to Equation 1, where $G_{day\,k}$ is the total day k electricity generation and n is the number of month days that presented PV generation measurements. The $G_{mth\,m}$ reveals the average amount generated per day by the PV DG in month m, its unit being kWh.

$$G_{mth\ m} = \frac{\sum_{k=1}^{n} G_{day\ k}}{n} \quad (1)$$

2.2. Daily average global irradiance

The overall monthly average daily radiation in the month m ($Ig_{mth\ m}$) is the average daily global irradiation with every day that showed measurements, according to Equation 2, wherein $Ig_{day\ k}$ is the total day k irradiation and n is the amount of days of the month that presented irradiance measurements. The $Ig_{mth\ m}$ reveals the average amount of irradiation at the site where the study is done, its unit being kWh / m².

$$Ig_{mth\ m} = \frac{\sum_{k=1}^{n} Ig_{day\ k}}{n} \quad (2)$$

2.3. Average capacity factor PV

One of the indices to be evaluated is the mean capacity factor PV (FC_{avg}) calculated according to Equation 3, the index is based on the value of the total electricity generated in a given time period (Eg_{total}) in kWh, the nominal power of the PV plant ($P_{nominal}$) in W and the time period analyzed (ΔT) in h. The FC_{avg} shows the ratio percentage of how much electricity was effectively generated in a given period of time in relation to how much energy could be generated if the PV DG always operated with the $P_{nominal}$.

$$FC_{avg} = \left(\frac{Eg_{total}}{P_{nominal} * \Delta T}\right) * 100\% \quad (3)$$

2.4. PV DG efficiency

The efficiency of PV DG (e_{PV}) is the ratio percentage of how much energy is generated by the PV system in relation to the incident solar irradiation, being calculated taking into account the total area of the PV modules. The system, under study, has a useful area (A_{DG}) of 9.7416 m².

$$e_{PV} = \left(\frac{Eg_{total}}{A_{DG} * Ig_{mth}}\right) * 100\% \quad (4)$$

2.5. Monthly sample standard deviation

The monthly sample standard deviation (s_m) is an absolute dispersion measure around the mean value of the data and has the same unit of the studied variable. The s_m reveals how scattered the measured data are in relation to the average in the interval of one month, that is, the smaller the s_m the smaller the monthly variability of the data. Equation 5 presents the formula for calculating this index, where $\bar{x}$ is the mean of the variable that the standard deviation is desired and x_i is the value of the variable in i.

$$s_m = \sqrt{\left(\frac{\sum_{i=1}^{n} (\bar{x} - x_i)^2}{n-1}\right)} \quad (5)$$

2.6. Monthly PV Pearson coefficient of variation

The monthly PV Pearson coefficient of variation (CVP_m) is a relative dispersion measure that shows the ratio of the standard deviation to the mean, being calculated by Equation 6.

$$CVP_m = \left(\frac{s_m}{\bar{x}}\right) \tag{6}$$

From CVP_m, which is a measure of relative dispersion, it is possible to classify the sample data collected, empirically, in dispersion levels, as shown in Table 1.

This coefficient is essential for an analysis of the intermittence, allowing an interpretation about different sample groups of the data, thus being able to compare datasets.

Table 1: The sample data Classification on the CVP_m basis

CVP_m Range	Data classification
CVP_m < 0,15	Low dispersion, homogeneous, stable.
0,15 ≤ CVP_m < 0,30	Average dispersion.
CVP_m ≥ 0,30	High dispersion, heterogeneous.

3. Materials

The present study was carried out in the PV DG system installed in the LEA (Alternative Energies Laboratory) at the Federal University of Ceará (UFC), Fortaleza, Brazil, with UTM (Universal Transverse Mercator) coordinates: latitude 3º44 '15' S and longitude 38º 34 " 22 " W, Figure 1 shows the LEA/UFC Location. The PV generation system has a nominal power of 1.5 kWp, consisting of 6 PV modules, from the manufacturer Yingli Solar, connected in series with individual power of 250 kWp. The modules have individual dimensions, 1.64 meters long and 0.99 meters wide, resulting in A_{GD} of 9.7416 m².

Figure 1: LEA/UFC Location.

Figure 2 shows the PV DG and the connection point - signaled by the red arrow - to the single-phase low-voltage power distribution network with a nominal voltage of 220 V from the Pici Campus/UFC. This connection is carried out by means of a frequency inverter, model PHB1500-SS, manufactured by PHB Electronics, designed for a maximum power of 1.8 kW, with nominal voltage of 220 V, unit power factor, maximum efficiency of 97 % and harmonic distortion rate less than 5%.

Figure 2: PV DG installed in the LEA / UFC and the network connection point of the Pici Campus.

The monitoring of the electricity generation data is carried out through a Datalogger, also of the PHB Eletronica, connected by RS485 communication to the inverter. The data is collected in each 10 minute and sent to storage on PHB's web server by the internet and made available for access in .xls format.

Similarly, local irradiance data are monitored by a data acquisition and control system, consisting of a programmable logic controller (PLC), Twido TWDLC-E40DRF, and a Hukseflux pyranometer model LP02, which is next to the PV DG. In order to acquire this data, the SCADA system was used with the PLC connected to a CPU (Central Processsing Unit) with a monitor.

The flowchart of the data acquisition systems are shown in Figure 3, the data of the two systems being accessed through the computer by .xls file.

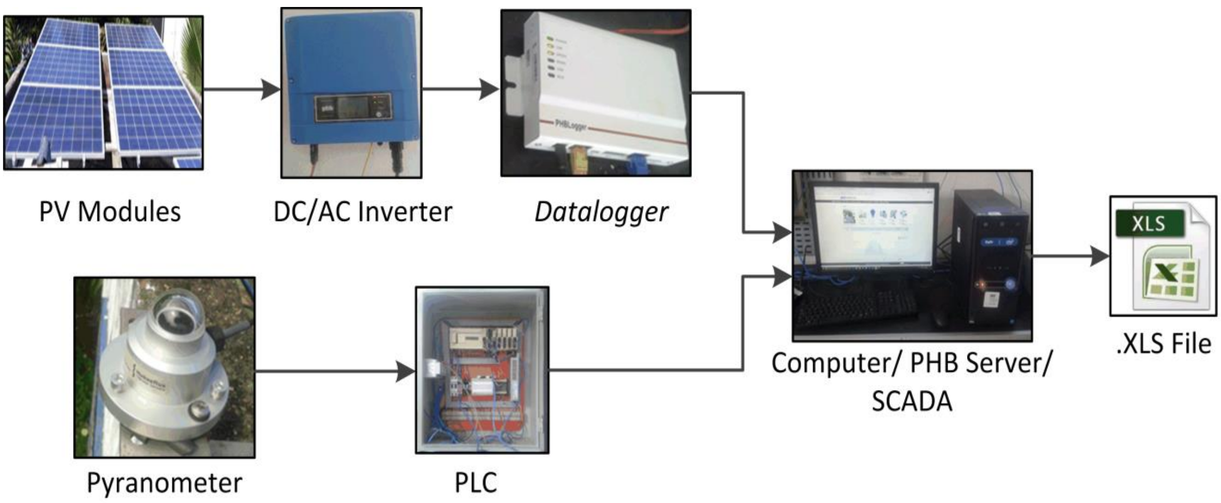

Figure 3: Data acquisition systems for electricity generation from PV DG and local irradiation.

4. Results and Discussion

In August, there were 31 days with irradiation measurements, with Ig_{mth} of 6.04 kWh/m², with s_{m_ig} of 0.4895 kWh/m² and CVP_{m_ig} of 0.0810. The CVP_{m_ig} shows that this month the daily irradiation has low dispersion, so the average represents well the measured data.

Figure 4 shows the irradiation behavior on the days of August; the highest irradiance was observed on 08/23/2017, with 6.65 kWh/m² and the lowest on 08/19/2017, with 4.38 kWh / m².

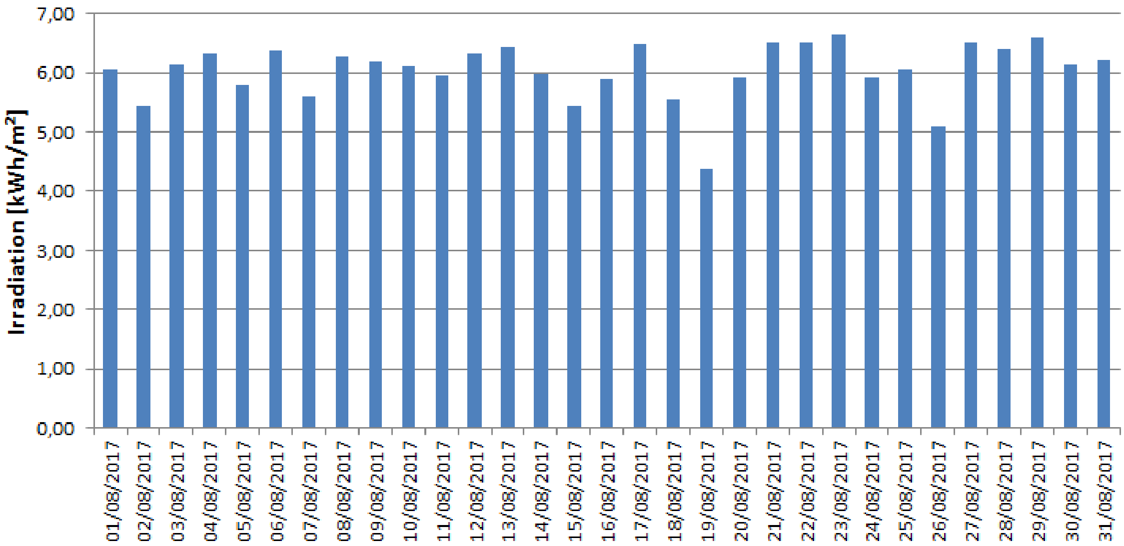

Figure 4: Average daily irradiation near the PV DG in August 2017.

There were 31 days with measurements of the electricity generated by the PV DG, with G_{mth} of 8.65 kWh, with s_{m_G} of 0.6366 kWh and CVP_{m_G} of 0.0736. The CVP_{m_G} show that this month the daily electricity generated has low dispersion. The PV FC_{avg} of August was 24.04%.

Figure 5 shows the behavior of PV DG on the days of August; the highest generation of electricity was observed on 08/23/2017 at 9.50 kWh and the lowest on 08/19/2017 at 6.60 kWh.

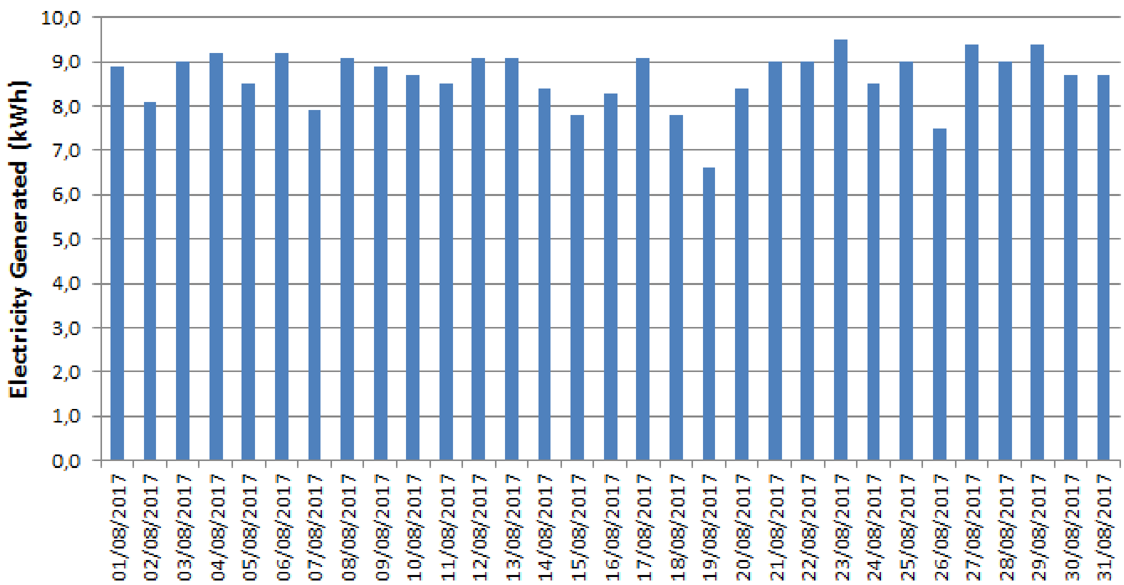

Figure 5: Electricity Generated per day by PV DG in August 2017.

The 10/08/2017 was chosen as the representative day of August, since FC_{avg} of the day was 24.17%, showing 5.04% greater than the FC_{avg} monthly. The irradiation of the day approaches Ig_{mth}, having irradiation of 6,12 kWh/m², that is, only 1.32% greater than Ig_{mth}. The electricity generated by PV DG was 8.70 kWh, only 5.78% lower than G_{mth}.

Figure 6 shows the behavior of PV DG and irradiation in August 2017 through the representative day. The PV power supplied, Figure 6.(a), tends to follow the irradiation curve, Figure 6.(b).

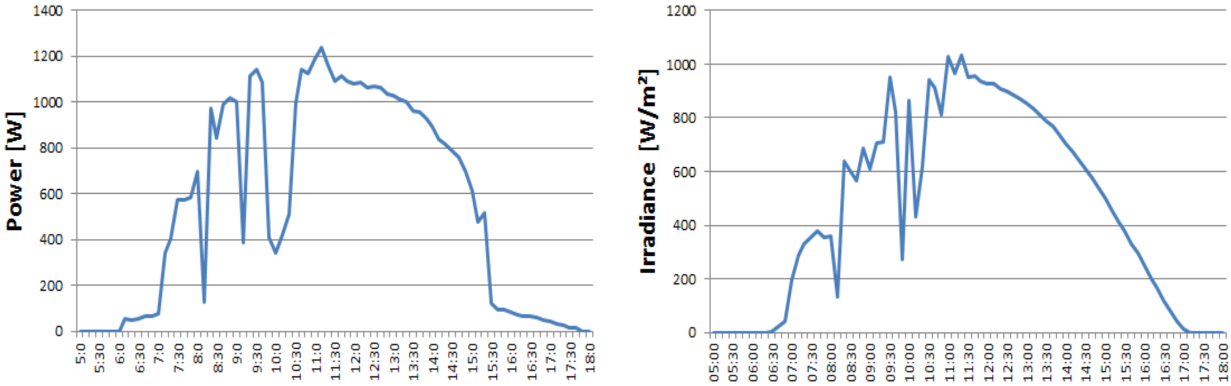

Figure 6: Curves for the August representative day (10/08/2017): (a) PV power supplied ; (b) Irradiation

Figure 6 shows a solar incidence with clouds in the morning and in the afternoon there is a direct and clean incidence – without clouds - until the period close to 18 hours. This shows a generation with fewer peaks in generation in the afternoon, precisely the peak hour period of the electric power system, thus helping to maintain system stability.

Table 2 shows in detail the data obtained from the PV DG installed in the LEA-UFC on the days of August 2017, with ΔG_{mth} being the generation in kWh/m².

The average e_{PV} in the month of August was 14.71%, close to the nominal e_{PV} of 15.40%. The highest e_{PV}, with a value of 15.47%, occurred on 08/19/2017, day with electric power generation of 6.6 kWh, FC_{avg} of the day was of 18.33% and irradiation of 4.38 kWh/m², and on this day the lowest irradiance of the month occurred, thus the lowest electricity generation, showing that e_{PV} does not depend only on irradiation.

The largest electricity generation was 9.50 kWh, obtained on 08/23/2017, with e_{PV} of 14.66%, which is below the monthly average.

The lowest e_{PV}, with a value of 14.15%, occurred on 08/21/2017, day with electric power generation of 9.0 kWh, FC_{avg} of the day was 25.00% and irradiation of 6.53 kWh/m², and this was a day with high FC, emphasizing, therefore, that besides the irradiation, the temperature of the panels also affect the e_{PV}.

Table 2: Data from PV DG installed on LEA-UFC in August 2017.

Day	ΔG_{mth} (kWh/m²)	G_{mth} (kWh)	Ig_{mth} (kWh/m²)	e_{PV} (%)	FC_{avg} (%)
01/08/2017	0,9136	8,9	6,07	15,05%	24,72%
02/08/2017	0,8315	8,1	5,45	15,26%	22,50%
03/08/2017	0,9239	9,0	6,14	15,05%	25,00%
04/08/2017	0,9444	9,2	6,31	14,97%	25,56%
05/08/2017	0,8725	8,5	5,79	15,07%	23,61%
06/08/2017	0,9444	9,2	6,38	14,80%	25,56%
07/08/2017	0,8110	7,9	5,60	14,48%	21,94%
08/08/2017	0,9341	9,1	6,28	14,87%	25,28%

09/08/2017	0,9136	8,9	6,18	14,78%	24,72%
10/08/2017	0,8931	8,7	6,12	14,59%	24,17%
11/08/2017	0,8725	8,5	5,94	14,69%	23,61%
12/08/2017	0,9341	9,1	6,32	14,78%	25,28%
13/08/2017	0,9341	9,1	6,42	14,55%	25,28%
14/08/2017	0,8623	8,4	5,98	14,42%	23,33%
15/08/2017	0,8007	7,8	5,44	14,72%	21,67%
16/08/2017	0,8520	8,3	5,90	14,44%	23,06%
17/08/2017	0,9341	9,1	6,49	14,39%	25,28%
18/08/2017	0,8007	7,8	5,55	14,43%	21,67%
19/08/2017	0,6775	6,6	4,38	15,47%	18,33%
20/08/2017	0,8623	8,4	5,93	14,54%	23,33%
21/08/2017	0,9239	9,0	6,53	14,15%	25,00%
22/08/2017	0,9239	9,0	6,51	14,19%	25,00%
23/08/2017	0,9752	9,5	6,65	14,66%	26,39%
24/08/2017	0,8725	8,5	5,94	14,69%	23,61%
25/08/2017	0,9239	9,0	6,05	15,27%	25,00%
26/08/2017	0,7699	7,5	5,09	15,13%	20,83%
27/08/2017	0,9649	9,4	6,51	14,82%	26,11%
28/08/2017	0,9239	9,0	6,42	14,39%	25,00%
29/08/2017	0,9649	9,4	6,60	14,62%	26,11%
30/08/2017	0,8931	8,7	6,15	14,52%	24,17%
31/08/2017	0,8931	8,7	6,22	14,36%	24,17%
Média	0,8884	8,65	6,04	14,71%	24,04%

Figure 7 shows the behavior of e_{PV} and FC_{avg} of the PV DG in the month of August 2017, also trying to show that, despite being counter intuitive, these two variables are not fully interconnected, making it more noticeable that a larger e_{PV} is not necessarily linked to a higher electricity generation by the PV system and also that there is not necessarily a high FC_{avg} when the e_{PV} is high.

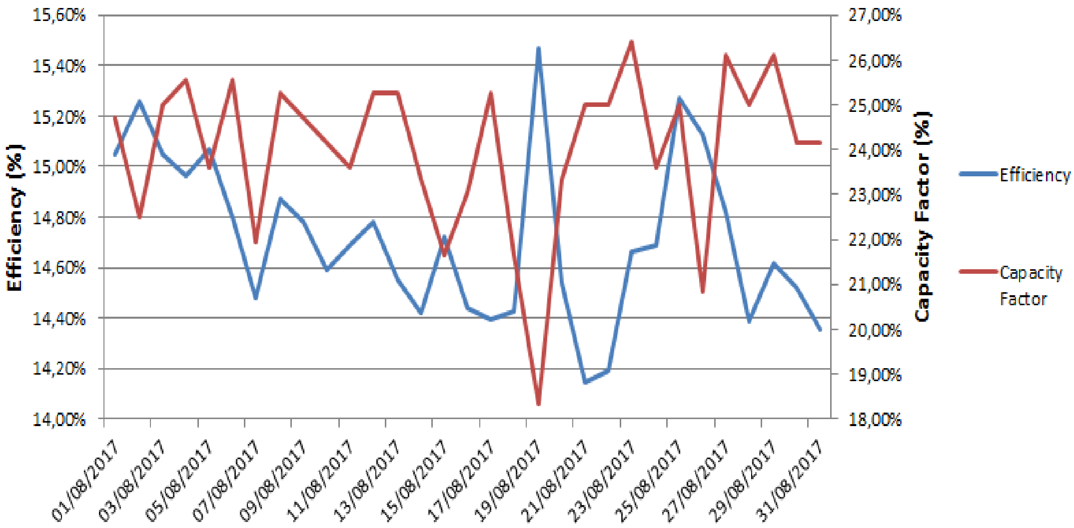

Figure 7: Behavior of e_{PV} and FC_{avg} of the PV DG in the month of August 2017.

Figure 8 shows that the electricity curve generated by m² of PV DG in the month of August 2017 tends to follow the local incident irradiation, so the higher the irradiation in the day, the better the electricity generation tends to be. Thus, e$_{FV}$ needs to be optimized based on parameters that do not affect the incidence of maximum local irradiance of a region.

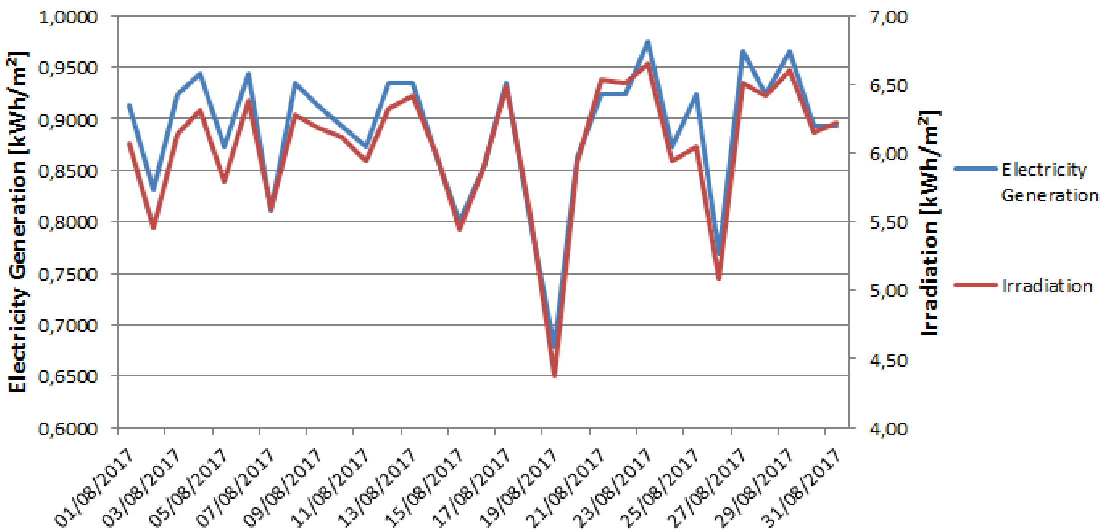

Figure 8: Behavior of the electricity generated by m² by the GV FV and the irradiation in the month of August 2017.

5. Conclusions

Knowing the generation profile of an energy source is essential for future energy planning and prospecting studies. The results obtained in the present study allowed us to draw a panorama of the generation of a PV DG in the month of August 2017 for the city of Fortaleza.

The month of August 2017 presented high values of global irradiation, with $Ig_{mês}$ 6.04 kWh/m², in a low dispersion band for irradiation, with CVP_{m_ig} of 0.0810, indicating an environment conducive to the exploration of a great solar potential.

The PV DG had a high electricity generation this month, reaching 8.65 kWh $G_{mês}$, with FC_{med} PV of 24.04%, in a low dispersion band for generation, with CVP_{m_G} of 0.0736, thus reflecting the high irradiance values of the region in which the study was carried out.

The e$_{FV}$ calculated on the days of the month of study revealed that high irradiation does not mean high efficiency. The highest efficiency measured was 15.47%, obtained on 08/19/2017, but the highest generation of electricity was 9.50 kWh, obtained on August 23, with a e$_{FV}$ of 14,66%, lower than the monthly average. Revealing that the premise of having a higher generation of electricity, due to high irradiance, is equivalent to a higher efficiency is not true, because other factors should be taken into account, such as panel temperature.

The 10/08/2017 was chosen as representative day, since the FC_{med} of the day was 24.17%, being the closest to the FC_{med} monthly. On this day the irradiation was 6.12 kWh/m² and the electricity generated by the PV DG was 8.70 kWh.

The daily profile of generation and irradiation, presented in Figure 5, eluded a characteristic peculiar to Fortaleza; in the morning, a solar incidence with clouds and in the afternoon a direct and clean incidence until near the 18 hours. Showing a more stable generation in the afternoon, just in the peak hour period of the electric power system, helping to maintain the stability of the system.

The panorama showed that the city of Fortaleza has good conditions for the exploration of solar energy. As future work, it is possible to relate other variables, such as panel temperature, ambient temperature and wind speed.

6. Acknowledgments

The authors are grateful to the Federal Institute of Education, Science and Technology of Ceara (IFCE), Cedro Campus, Federal University of Ceara (UFC), the University Center September 7 (UNI7), the Coordination for Improvement of Higher Education Personnel (CAPES) and the Laboratory of Alternative Energies of the UFC (LEA).

7. References

ANEEL. 2011. Chamada Nº 013/2011 Projeto Estratégico: "Arranjos Técnicos e Comerciais para Inserção da Geração Solar Fotovoltaica na Matriz Energética Brasileira". Agência Nacional de Energia Elétrica.

ANEEL. 2012. Resolução Normativa Nº 482, de 17 de Abril de 2012. Agência Nacional de Energia Elétrica.

Barbosa, E. M. D.; Uribe, F. B.; Figueiredo, T. M.; Freitas, D. S.; Mascarenhas, A.C.; Vilela, O. C.; Tiba, C. 2014. Índices de produtividade na montagem de Usinas Fotovoltaicas no Brasil. Estudo de Caso – Usina Solar Fotovoltaica São Lourenço da Mata. V Congresso Brasileiro de Energia Solar.

Costa, D. A. C.; Carvalho, P. C. M.; Cavalcante, A. P. H.; Soares, F. S.; Vieira, O. L.; Silva, F. J. R.; Barroso, G. C. 2017. Performance de uma Geração Distribuída Fotovoltaica Instalada na Zona Urbana de Fortaleza. 2º Congresso Brasileiro de Geração Distribuída. Fortaleza.

Cresesb. 2000. Atlas Solarimétrico do Brasil: banco de dados solarimétricos. Centro de referência para energia solar e eólica Sérgio Brito. Recife.

EPE. 2017. Balanço energético Nacional 2017 com no ano base 2016: Resultado final.

Frate, C. A.; Brannstrom, C. 2017. Stakeholder subjectivities regarding barriers and drivers to the introduction of utility-scale solar photovoltaic power in Brazil. Energy Policy. Vol. 111, pp. 346-352.

Global Market Outlook. 2017. For Solar Power / 2017 -2021. Solar Power Europe.

L. Cadavid; C. J. Franco. 2017. Impact of Currency Devaluation on the Grid Parity for Residential Solar Generation in Latin America. IEEE Latin America Transactions. Vol. 15, Nº. 11.

Lima, L. C.; Ferreira, L. A.; Morais, F. H. B. L.. 2017. Performance analysis of a grid connected photovoltaic system in northeastern Brazil. Energy for Sustainable Development. Vol. 37. pag. 79-85.

Lo Piano, S. and Mayumi, K. 2017. Toward an integrated assessment of the performance of photovoltaic power stations for electricity generation. Applied Energy, 186, pp.167-174.

P. P. Barker, J. M. Bing. 2005. Advances in solar photovoltaic technology: an applications perspective. IEEE Power Engineering Society General Meeting. Vol. 2, pp. 1955-1960.

Shimura, S.; Herrero, R.; Marcelo Knorich Zuffo, M. K; Jose Aquiles Baesso Grimoni, J. A. B. 2016. Production costs estimation in photovoltaic power plants using reliability. Solar Energy. Vol. 133, pp. 294-304.