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Performance Analysis of a 3.2 kWp Photovoltaic System with Microinverter for Distributed Generation

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***Keywords*— Distributed Generation, Microinverter, Performance Analysis, Photovoltaic Solar System.**

***Abstract*— *Faced with the increase in electricity consumption and in the tariffs of the kWh consumed, as well as the insertion of renewable sources in the world energy matrix, several countries seek to encourage industrial, commercial and residential consumers to invest in distributed generation systems. In Brazil, ANEEL Resolution No. 482 of 2012 and later updated by No. 687 of 2015, aims to establish distributed mini and microgeneration from renewable sources such as photovoltaic solar energy. Distributed generation is advantageous both for local utilities, as it provides a reduction in grid loading, minimization of losses and diversification of the national energy matrix, among others, and for the consumer who, through the provided compensation system, will be able to inject the surplus energy generated into the electricity grid of the local energy concessionaire and, with that, it will earn a bonus on your electricity bill at the end of the month. Considering that Brazil is mostly located in the intertropical region, for exemple, the Northeast region, where the sun is present most of the year. Thus, this study aims to present an evaluation of the local solar resource and the performance indexes related to a photovoltaic system connected to the 3.2 kWp grid with microinverter in a low voltage residence in Fortaleza-CE.*

I. INTRODUCTION

Electricity generation in Brazil is highly dependent on hydroelectric plants and, facing the worst water crisis of the past 91 years, the lower levels of rain reduced the water reservoirs to critical levels and aggravated the situation of the country during the fight against the COVID-19 pandemic. This fact made the Brazilian government increase the generating capacity of thermoelectric plants, which increased the electricity bills for Brazilian people due to the fact that the kilowatt-hour (kWh) generated by the thermoelectric plants is more expensive compared to hydroelectric [1].

According to the Instituto de Pesquisa Econômica Aplicada (Applied Economic Research Institute), the increase of industrialization, population density, urbanization, and mass consumption of industrialized products demand that companies, governments, and consumers, in general, invest in renewable energy sources with low environmental impact aiming to meet the current energetic needs that do not impact future generations' capacities [2].

Besides those problems, the debates about climate change became the topic of conferences and forums around the world, since it is necessary to discuss the future of development considering the urgency of adopting strategies focused on electricity generation that does not impact the environment. In this scope, renewable energy sources are an option to change the worldwide energetic matrix and a way to avoid scarcity of resources such as oil and derivatives [3].

According to [4], one of the possibilities found to reduce the costs of electricity in Brazil is the exploration of photovoltaic systems, aiming to generate energy through a renewable and sustainable source. Brazil is mostly-located in the intertropical region and has a great potential to explore solar energy all year. The Northeast part of the country, for example, receives high levels of sunlight most period of the year and attracts investments for the sector. According to [5], the use of solar energy brings long-term benefits to the country, enabling the development of remote regions where the costs of electrification with the conventional grid are excessively high compared with the financial return of the investment.

Distributed generation (DG) is, by definition, the electricity generation produced near the consumer(s), regardless of its potency, technology resources, and energy source. It is worth highlighting that, until 2012, DG did not have much promotion in Brazil compared to other countries. Aiming to regularize and encourage the implementation of these systems, the government created the Regulatory Standard 482/2012 (RN 482/2012), lately updated by RN n° 687 in 2015. The referred resolution allows any electricity generator unit to distribute to the energy providers through their grids and created the modalities microgeneration (with an installed power of ≤ 75 kW) and distributed microgeneration (installed power > 75 kW ≤ 3 MW for water sources or ≤ 5 MW for other renewable energy sources), in which consumers receive credits with the energy provider of the region to use when necessary [6], [7].

On the world stage, solar photovoltaic power generation increased 22% in 2019, representing 131 TWh, becoming the second increase in renewable energy resources behind wind power. In Brazil, photovoltaic plants represent 1,68% of the energetic matrix but it is important to highlight that the plants whose constructions were and are yet to be initiated are, respectively, 5,68% and 43,50% of the power bestowed, showing, thus, a tendency of growth on the application of solar photovoltaic energy [8], [9].

It is worth highlighting that, before the installation and the correct functioning of the DG with solar photovoltaic energy, it is necessary to evaluate the factors that might directly affect the power generation, such as shadowing, inclination, misdirection or poor location, maintenance of the cables and inverter, among others. In this sense, it is essential to analyze the main factors liked to the project and performance of a grid connected photovoltaic power system (On Grid), in order to avoid possible losses and, therefore, preserve the system. Therefore, this study aims to show the performance of a 3,2 kWp grid connected photovoltaic system with a micro-inverter installed in a house in Fortaleza, Ceará, Brazil.

II. THE GRID CONNECTED PV SYSTEM

The grid connected photovoltaic system analyzed in this study is connected to the grid of the local energy provider ENEL-Ceará. The single-family house consumer belongs to the low tension (LT) single-phase (220 V) tariff group. The distributed microgeneration solar photovoltaic system follows ANEEL's RN n° 482/2012 and RN n° 687/2015 standards as well as ENEL's Technical Standard (TS). The system operation started on March 2021 and its coordinates are latitude: -3.719076 S/longitude: -38.563698 W (decimal degrees).

According to the technical requirements for the connection of micro and mini on grid generations, it is necessary to estimate the total installed power considering the potency of all the pieces of equipment at the Consumer Unit (CU), the total installed power of the house was 6.738 kW. Thus, the proposed topology for the photovoltaic system was 08 photovoltaic solar modules with a total array area of 17,43 m^2, a calculated unit power (kWp) of 5,54 m^2, and a maximum nominal power of 3,2 kWp installed on the roof of the building.

The photovoltaic solar module selected for the GCPVS was DAH HCP78X9 POLI 400 W made of polycrystalline silicon pointing to the North at a 10º azimuth angle. The two microinverters are the MI-1500 model by HOYMILES with a 25-year lifespan and maximum rated efficiency from 96,7 to 97, 2% according to the manufacturer. The installation was in a covered space, allowing the sheltering of the conversion installation as well as the protection of the system from weathering and unauthorized access.

III. PERFORMANCE PARAMETERS

The evaluation of a grid connected photovoltaic system usually follows the Standard IEC 61724. The evaluated parameters were: energy output, yield (reference, array, and final), energy losses of the array and of the system, system efficiencies (array efficiency, system efficiency, and inverter efficiency), performance ratio, and capacity factor [10]-[12].

Energy output

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

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

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

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

In which $E_{AC,t}$ 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

$$Y_F = \left(\frac{E_{CC}}{P_{pV.nom}}\right) . \left(\frac{kWh}{kWp\ .dia}\right) \qquad (5)$$

month.

System yield

There are three types of system yields, which are: reference yield (Y_R), PV array yield (Y_{PV}), and final yield (Y_F). They represent the energy generated, in kWh, for each kWp of installed power. The unit to represent the yields is kWh/kWp.day or in hours/day. When expressed in hours/day, it represents the time the system should operate in its nominal power to generate the same amount of energy in the same given period of time. The yields indicate the real operation of the photovoltaic modules and the photovoltaic array in relation to its nominal power. The PV array yield (Y_{PV}) is given by equation 10, in which E_{DC} is the total energy (in kWh) produced by the photovoltaic array [13].

$$Y_{pV} = \left(\frac{E_{CC}}{E_{CC.nom}}\right) . \left(\frac{kWh}{kWp\ .dia}\right) \qquad (4)$$

The final yield Y_F is given by equation 5, in which E_{AC} represents the total AC energy and the nominal power of the photovoltaic modules is $P_{PV.\ nom}$.

The reference yield Y_R is the total irradiation on the level or the 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:

$$Y_R = \left(\frac{H_T}{H_R}\right) . \left(\frac{kWh}{kWp\ .dia}\right) \qquad (6)$$

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:

$$Y_R \geq Y_{FV} \geq Y_F \qquad (7)$$

System energy losses

The capture 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 [13]. The calculation of the PV array capture loss is the difference between the reference production of the photovoltaic panels. It is given by equation 8:

$$L_{pV} = Y_R - Y_{pV} \left({}^{kWh}/_{kWp}\right) \qquad (8)$$

The losses of the 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:

$$L_S = Y_{pV} - Y_F \left({}^{kWh}/_{kWp}\right) \qquad (9)$$

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:

$$L_T = L_{pV} + L_S \left({}^{kWh}/_{kWp}\right) \qquad (10)$$

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 on an instant, hourly, daily, monthly and annual basis, expressed in percentages [13].

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 [14]. The system efficiency is given by equation 12 and the inverter efficiency by equation 13. Considering A_{PV} the total area of the photovoltaic array in m^2 and P_{PV} the potency of the PV array:

$$\eta_{pV} = \frac{100\ x\ P_{pV}\ x\ Y_{pV}}{Y_R\ x\ A_{pV}} \quad (11)$$

$$\eta_{SYS} = \frac{100\ x\ E_{CA}}{H_T\ x\ A_{pV}} \quad (12)$$

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

Performance ratio

According to [13], performance ratio (P_R) is a quality measure of a photovoltaic system that is regardless of its localization and, in many occasions, is described as a quality factor. Expressed in percentage, it shows the relationship between the real and theoretical outputs of the GCPVS. Thus, it shows the amount of energy really available to input on the grid after the deduction of the losses and energy consumed for this operation.

The closer to 100% the P_R is, the lower the system losses. However, it is not possible to reach 100% P_R in reality since there are inevitable losses that happen during the performance of a PV system. With the P_R, it is possible to compare the energy output of your own photovoltaic system with other photovoltaic systems in any geographic localization. The performance ratio, seen in equation 9, is the final ratio between the final yield of the photovoltaic system (Y_F) and the reference yield (Y_R), expressed in percentage, as seen in equation 14 below [14]:

$$P_R = \frac{Y_F}{Y_R}\ x\ 100\% \quad (14)$$

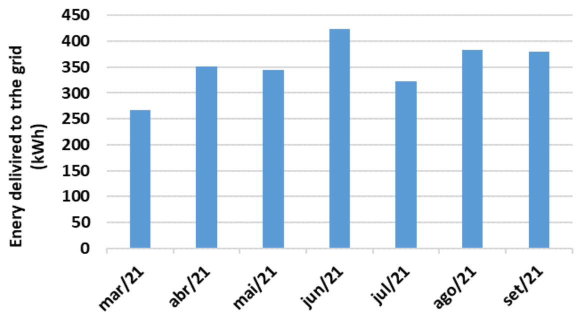
Capacity factor

The capacity factor (FC) is, by definition, the relation between the real annual AC total power productivity and the amount of power the PF array would produce if it operated with a total power ($P_{FV,\ nom}$) for 24 hours a day for a period of a year, according to equation 15.

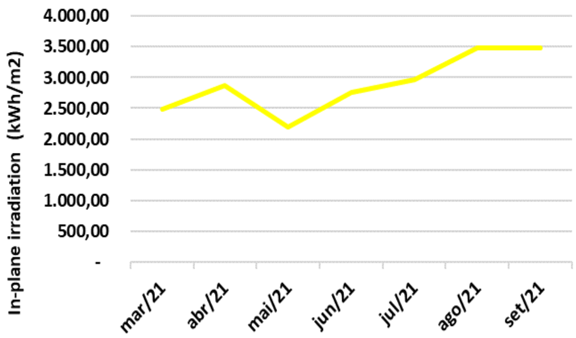
$$FC = \frac{E_{CA}}{P_{pV,nom}\ x\ 8760} (\%) \quad (15)$$

IV. RESULTS AND DISCUSSION

According to the graphic on Fig. 1 (a), the total power produced from March to September 2021 was 2,47 MWh, with a monthly average of 353,09 kWh. According to the report of the national energy balance (EPE, 2021), the average consumption in the residential category in the Northeast in 2021 was 128 kWh/month. Thus, the GCPVS in this study delivers, on average, energy equivalent to 2,76 houses per month. The total radiation during the period was 20.247,22 kWh/m2, with a monthly average of 2892,46 kWh/m2. The highest amount of energy produced was in November/2021 (433,25 kWh) and the lowest was in March/2021 (267, 27kWh). The lowest level of solar irradiation was in September (3.485, 33 kWh/m2), during the dry rainless season. March/2021 was the month with the lowest irradiation levels (2.196,13 kWh/m2), as seen in Fig. 1 (b).



(a) Energy produced by the GCPVS.



(b) Irradiation on the horizontal level.

Fig. 1: Energy produced by the photovoltaic system and irradiation on the horizontal level.

It is worth highlighting that the monitoring of the photovoltaic system is realized by electronic equipment that sends information about the photovoltaic system to a digital platform. A frequent inverter captures the data and sends it online, in real-time, to the manufacturer's website. Thus, the user can follow and monitor on daily basis information such as the performance as well as the daily, monthly and annual economy. It is also possible to verify with live data eventual failures on the performance, which allows fixing in a timely manner.

Thus, by comparing the monthly energy consumption in the building and also the electricity bills, we collected the costs from March to September 2020 and 2021. Table 1 shows the monthly consumptions in kWh/month (according to the amounts shown in the electricity bill) and the respective cost in Reais. The GCPVS operates since March 2021 and, when compared to March 2020 before its installation, it was possible to verify a reduction in the electricity consumption. This happened due to the reduction in the excess power imputed on the grid of the energy provider which resulted in the credit compensation described on the RN 482/2012 showing, therefore, the benefits of adopting the distributed energy generation system using renewable energy sources.

Table.1: Comparison between the 2020-2021 electricity bills.

2020	Monthly consumption (kwh)	Electricity bill	2021	Monthly consumption (kwh)	Electricity bill	Difference on the consumption with the pvs
Mar	378	R$ 339,30	Mar	158	R$ 127,89	58,2%
Apr	485	R$ 421,28	Apr	313	R$ 172,41	35,46%
May	384	R$ 343,91	May	337	R$ 227,19	12,24%
Jun	437	R$ 384,61	Jun	307	R$ 108,85	29,75%
Jul	358	R$ 323,94	Jul	296	R$ 142,63	17,32%
Aug	345	R$ 313,96	Aug	285	R$ 125,38	17,39%
Sep	315	R$ 290,92	Sep	275	R$ 120,38	12,7%

Comparing the period from March to September/2021, the seven months after the installation of the GCPVS, it was possible to notice an economy of R$ 1.393,19. Therefore, in seven months, the GCPVS allowed a reduction in energy consumption and, consequently, a reduction in the electricity bill. it is essential to highlight that there are many other benefits linked to the use of distributed energy using renewable sources, such as the reduction of greenhouse gas emissions; reduction of the expansion of huge generation installations; reduction of the use of non-renewable energy sources; an increase of supply reliability; reduction on the transmission and distribution losses; contribution to local development; faster answer to an increase of the demand; cost reduction with the energy provider; and appreciation of the building or business.

The monthly average yields are in Fig. 2, which highlights the reference yield (Y_R), PV array yield (Y_{PV}), and final yield (Y_F). It is possible to observe that the lowest values were in May 4,03 kWh/kWp/day; 3,60 kWh/kWp/day, and 3,48 kWh/kWp/day, respectively. On the other hand, the highest values were in September, 6,60 kWh/kWp/day; 4,10 kWh/kWp/day, and 3,96 kWh/kWp/day, respectively. The monthly average of the seven-month period were 5,38 kWh/kWp/day; 3,74 kWh/kWp/day, and 3,61 kWh/kWp/day, respectively. According to [14], the lowest yield rates occurred during the rainy season in the Northeast, between February and May. While the rates between June and January are superior to the rainy season due to the dry climatic conditions and the solar irradiation on the level.

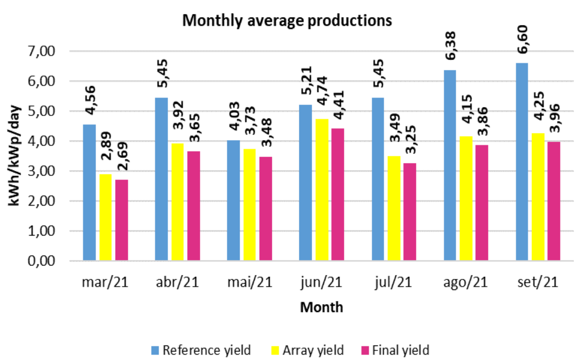


Fig. 2: Monthly average YR, YFV, and YF yields.

Comparing this study with [14] that registered its lowest level in April with 4,5 kWh/kWp/day, 3,9 kWh/kWp/day, and 3,7 kWh/kWp/day, respectively, the differences are 0,47 kWh/kWp/day; 0,3 kWh/kWp/day, and 0,22 kWh/kWp/day, respectively. On the other hand, the highest YR rate was in October with 6,5 kWh/kWp/day, a difference of 0,1 kWh/kWp/day; while the YPV and YF rates in September were 5,8 kWh/kWp/day and 5,5 kWh/kWp/day, a difference of 1,7 kWh/kWp/day and 1,89 kWh/kWp/day, respectively. It was possible to infer that the difference is linked to the azimuth orientation, in which this study shows a 10º while [14] has a 0º azimuth.

The monthly average efficiencies estimated for the photovoltaic system are in Fig. 3. The average inverter efficiency was 98% from March to September/2021, close to the highest theoric level described by the manufacturer. The monthly average rates for the system and the array were 12,71% and 12,43%, respectively. The highest system and array efficiencies were in May with a 16% rate.

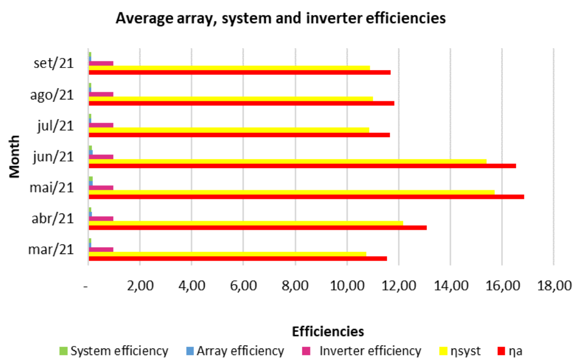


Fig. 3: Monthly average efficiencies.

In the study by [14], the monthly average array, system, and inverter efficiencies were 13,3%, 12,6%, and 94,6%, respectively. The highest matrix, system, and inverter efficiencies were 14,8% (in August), 13,9% (in August), and 95,3% (in July), respectively. Thus, it is possible to notice a slight percentual difference between the studies. The authors link this factor to shadowing that caused a reduction in the matrix, system, and, possibly, the inverter efficiencies. The performance ratio (PR) showed variation between 59,11% in March/2021 to 86,35% in May/2021 and an annual average of 68,19%. 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 energy provider (ENEL) which avoids the binding of the GCPVS. Lastly, the capacity factor (CF) varied between 11,23% (March/2021) and 18,39% (June/2021), with an average of 15,06%, this factor aimed to measure the average percentage in which the GCPVS operated at full capacity, as shown in Fig. 4 [13].

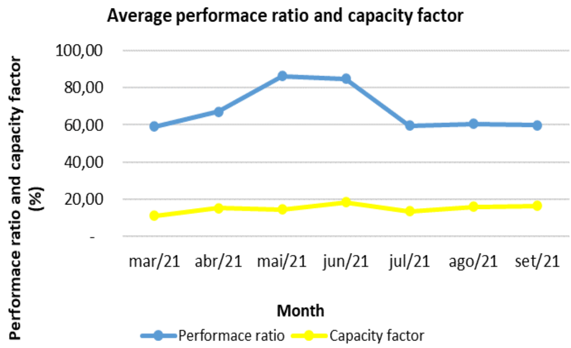


Fig. 4: Monthly averages CF and PR.

Fig. 5 shows the relative losses of the studied GCPVS. The month with the highest loss was September/2021 with 2,64 kWh/kWp/day and the lowest was in May/2021with 0,55 kWh/kWp/day. In all the months of the study, the array loss (that represents the losses due to the operation that highlights the incapacity of the photovoltaic array in fully using the available irradiation) surpassed the system loss (losses that occurred due to the conversion of direct current output to alternating current by the inverter also considering the losses caused by joule effect). It is also necessary to consider that the GCPVS is oriented to a 10º azimuth and this condition might increase the losses on the photovoltaic panels due to the failure of direct radiation capture, according to the relative solar movement. According to [15], 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.

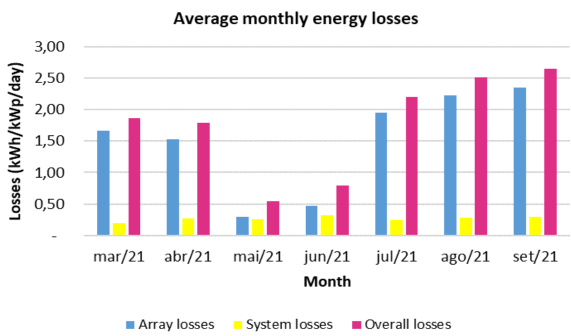


Fig. 5: the relative losses of the GCPVS

V. CONCLUSION

This study showed the analysis of a distributed generation system of a house located in Fortaleza/CE that used the local solar resources aiming to reduce the costs of the electricity bill by using the credit compensation system included on the RN 482/2015. Thus, the collection of the installed loads and the evaluation of the local irradiation on the horizontal level indicators sent by FUCEME/CE which contains the climate conditions of the Brazilian Northeast region. The project of the 3,2 kWp GCPVS and the evaluation of its performance indicators were analyzed in a way that standardized the localization as a basic variable, such as solar irradiance, maintenance, temperature, and shadowing, among others.

According to the analysis, the GCPVS delivered to the grid a monthly output of 353,09 kWh (March/2021 to September/2021), an amount over the average consumption in the Northeast region of Brazil 128 kWh/month and equal to the consumption of 2,76 construction/month. Besides that, the monthly average radiation of the analyzed period was 2892,46 kWh/m^2. We also analyzed the electricity bills of the building from March and September in 2020 (without the GCPVS) and 2021 (after the installation) in a period of seven months the system provided an economy of R$ 1.393,19, since the spare energy was input into the grid of the local provider and, by the credits compensation, it was possible to have a discount on the electricity bills.

Besides that, we calculated the estimates of the average efficiency of the system and of the array considering the data on the microinverter. Thus, the average system efficiency was 12,71% and the average array efficiency for the same period was 12,43% for the period from March to September 2021. We also calculated the estimated performance ratio and the capacity variation, the performance ratio had an annual average of 68,19% while the capacity factor was 15,06%. The relative losses of the GCPVS showed a higher loss in September/2021 with an amount of 2,64 kWh/kWp/day and a lower amount in May/2021 with 0,55 kWh/kWp/day.

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