Energia sustentável na agroindústria: avaliação, homologação e funcionamento de um sistema de energia solar fotovoltaica na geração distribuída do Paraná

Sustainable energy in agroindustry: evaluation, homologation and operation of a photovoltaic solar energy system in distributed generation of Paraná

DOI:10.34117/bjdv8n4-554

Recebimento dos originais: 21/02/2022
Aceitação para publicação: 31/03/2022

Danilo Hungaro Micheletti
Mestre em Bioenergia
Instituição: Universidade Federal do Paraná (UFPR)
Endereço: Rua Pioneiro, 2153 - Dallas - CEP: 85950-000 - Palotina - PR
E-mail: danilohmicheletti@hotmail.com

Joel Gustavo Teleken
Doutor em Engenharia Química
Instituição: Universidade Federal do Paraná (UFPR)
Endereço: Rua Pioneiro, 2153 - Dallas - CEP: 85950-000 - Palotina - PR
E-mail: joel.teleken@ufpr.br

RESUMO
A energia é um dos pilares fundamentais de todos os setores da sociedade contemporânea. No entanto, os impactos ambientais relacionados às fontes de energia não renováveis têm afetado diretamente o planeta e sua população. Assim, a conversão fotovoltaica da energia solar se generalizou devido aos avanços tecnológicos. Nesse contexto, é cada vez maior o interesse em instalar sistemas de maior porte em indústrias da região Noroeste do Paraná, com o objetivo de economizar energia elétrica e aumentar a sustentabilidade de suas empresas. Assim, este trabalho é um estudo de caso do processo de implantação de um sistema de energia solar fotovoltaico aplicado em uma indústria de laticínios da Geração Distribuída brasileira no porte da Minigeração, com potência instalada de 100 KW. A pesquisa foi exploratória e descritiva, baseada em observações e experiências. A pesquisa se mostra importante a fim de elucidar os aspectos técnicos da Minigeração Distribuída vigentes no Brasil, expondo seu processo de aprovação de projetos.

Palavras-chave: geração de energia, sustentabilidade, avanços tecnológicos, energias renováveis.

ABSTRACT
Energy is one of the fundamental pillars of all sectors of contemporary society. However, the environmental impacts related to non-renewable energy sources have directly affected the planet and its population. Thus, the photovoltaic conversion of solar energy has become widespread due to technological advances. In this context, there is growing interest in installing larger systems in industries in the Northwest region of Paraná, to
save electricity and increase the sustainability of their companies. Thus, this work is a case study of the process of implantation of a photovoltaic solar energy system applied in a Brazilian Distributed Generation dairy industry in the size of Minigeração, with installed power of 100 KW. The research was exploratory and descriptive, based on observations and experiences. The research proves to be important to elucidate the technical aspects of Distributed Minigeneration in force in Brazil, exposing its project approval process.

**Keywords:** power generation, sustainability, technological advancements, renewable energy.

### 1 INTRODUCTION

Brazil has one of the largest hydroelectric potentials in the world and most of the national electricity matrix currently comes from this resource. However, hydropower is not a source free of atmospheric emissions and most of possible new projects are available only in the Amazon basin region, but they would cause interferences with environmental protection areas or social occupation. (ANEEL, 2005; Becker, 2012).

In addition, drought periods in several regions of the country promote an energy deficit, which pressures the national interconnected system to use fossil fuel-fired thermoelectric plants to meet demand. Therefore, there is no forecast of a significant increase in installed hydroelectric generation capacity since 2018, but only in the increasing share of other renewable sources of electricity generation (Tolmasquim, 2016).

Distributed generation modality connects power sources close to the consumption points to the distribution network. It enables the implementation of several intermittent sources of energy to produce electricity, enabling better energy use from sources such as solar and wind energy. So, the places that have this type of generation are saving whenever they consume the energy generated right there (Dantas; Pompermayer, 2018).

In Brazil, distributed generation was regulated in 2012 by the Brazilian National Electric Energy Agency (ANEEL), through the Normative Resolution (RN) No. 482, establishing the approval criteria for access to the grid and the general conditions for energy compensation. It allows consumers to exchange the energy generated in the grid-tie mode, creating the rules for a system that compensates the consumer for the electric energy injected into the grid (ANEEL, 2012; COPEL, 2021; Rüther *et al*., 2008.).

In 2015, the regulation was improved by RN No. 687, making the connection process faster, improving the credit system and making the distribution of credits among consumer electric units more flexible. For distributed generation currently regulated in
Brazil, the connection of generators up to 5 MW in the grid is permitted only if they are renewable energy sources (ANEEL, 2012).

So, the life quality of the population can improve with sustainable economic growth through the planned and efficient use of available energy resources. Among the ways of harnessing sunlight, Photovoltaic (PV) conversion of solar energy has become widespread due to technological advances in equipment manufacturing and the versatility in building systems integrated into consumer electric units or large-scale production plants (European Commission, 2009; Hinrichs, 2010).

According to TIEPOLO et al. (2017), Brazil has excellent solar irradiation rates for electricity generation. So, PV solar energy applied in distributed generation connections have become popular in the Brazilian electricity sector and worldwide, with many benefits for users. Also, transformerless string inverters process energy in smaller groups of PV panels and allows multiple Maximum Power Point Tracking (MPPT) in a PV system with different orientations, rising the flexibility of its use (Kjaer et al., 2005; Thomson; Infield, 2007).

This research elucidates technical aspects of a photovoltaic system with installed power of 100 kW in the Brazilian normative regulations. It contributes with information regarding the development and implementation of a generator system of this size. The general objective was to evaluate and expose a photovoltaic solar system implementation in the Brazilian Distributed Mini-generation mode in an agroindustry.

2 CASE OF STUDY METHODOLOGY

The object of study is the dairy industry called “E. F. Arantes e Cia Ltda”, in the city of Nova Cantu in Paraná state, which produces milk, butter and cheeses in a modern automatic production system. The owner had interest in the implementation of a distributed PV solar energy system due to the constantly growing energy costs. The opportunity to increase the company's sustainability was also interesting. The case study as a research strategy allows further research with direct observation, building a more contextualized and contemporary understanding of the issue (Yin, 2001).

An exploratory and qualitative field research was carried out, using systematic observation. It provided understanding and clarification for the analysis. Investigation strategies were implemented, such as the collection of information, in addition to the survey of bibliographic and technical material. Then, the research steps were observed as seen in Figure 1 in way to fulfill the objectives. Each one of those three steps are explained
in the following chapters. The homologation process took place in September 2019 and the production analysis were made for the three subsequent months (Flick, 2013).

3 PREVIOUS STUDY
3.1 CONSUMER UNIT CHARACTERISTICS

This accessor substation, as seen in Figure 2, was a larger electrical input unit with owner transformation. In this case, it has a 300kVA star-triangle transformer to convert from the 13.8kV distribution line to the 127/220V consumption local standard. It has the indirect measurement type with Current Transformers (CT) and has a 500A three-phase general circuit breaker. The electric service of this consumer electric unit is Parana’s Energy Company (COPEL), and the metering has telemetry to send remotely measuring information.
This consumer electric unit belongs to group A, with voltage supply greater than 2.3kV. Its consumption is charged in the green time-zone mode, differing prices for peak and off-peak hours. Thus, from COPEL (2019), its energy consumption is characterized as peak from 6 pm to 9 pm, now costing R$1.97 per KWh, and as off-peak, costing R$0.52 per KWh. The average consumption recorded for peak was 947KWh and for off-peak was 17,507KWh, as seen in Figure 3.

This consumer electric unit has a previously contracted power demand of 90kW. It was observed an exceeded demand in most months, as seen in Figure 4, paying a double cost penalty on the exceeded amount. Therefore, a new contract for demand was made with an adequate value of 100kW.
3.2 PV SYSTEM APPLIED

RN No. 482 by ANEEL (2012) states that Mini-generation mode must have an output power generation equal to or less than the contracted power demand of the consumer unit. Thus, in order not to higher the bill costs and to generate at least 60% of the off-peak energy of the dairy industry, the chosen total output power of inverters was 100KW (COPEL, 2021).

So, the system had four units of Eco 25.0-3-S from Fronius (2020). Each inverter has 25 kW power output, 1 MPPT 6-string Direct Current (DC) input and three-phase Alternate Current (AC) output at 380 Volts phase-to-phase and 60 Hz frequency in the Brazilian configuration. According to Fraunhofer Institute (2021) those inverters have large local market share and allow the use of more than one MPPT in the plant.

Then, to maximize generation, it was used 123.75 KWp of array power, an oversizing allowed by the manufacturer and compatible with the existing roofs. The 375 modules used were from Canadian Solar (2016), model MAXPOWER CS6U-330P. It is a 72-cell polycrystalline type with rated power of 330 Wp under Standard Test Conditions (STC) conditions, with 16.97% modulus efficiency and with 5 busbar cell technology.

3.3 LOCAL TEMPERATURES EVALUATION

Nova Cantu has typical minimum Ambient Temperature (T_a) of 0ºC in winter and maximum T_a of 36ºC in summer (ACCUWEATHER, 2020). The worst case of evaluation is considered with wind speed of 0 m/s². Thus, Yang et al. (2018) showed that Lasnier and Ang (1990) equation provides a good estimative for PV cell temperature, with low error. So, (1) was used to find Photovoltaic Cell Temperature (T_c) from T_a.
\[ T_c = 30,006 + 0,0175(G - 300) + 1,14(T_a - 25) \]  

From the maximum \( T_a \) of 36ºC and considering the highest Total Irradiance (G) of 1000 W/m\(^2\) for a summer day, the maximum \( T_c \) found was 55ºC. From the minimum \( T_a \) equal of 0ºC and considering a high G of 800 W/m\(^2\) for a winter day, the minimum \( T_c \) found was 10ºC. These are the extreme limits in maximum conditions and are used to correctly check the PV system disposal, avoiding overvoltage problems and loss of efficiency during production.

### 3.4 TEMPERATURE EFFECT ON MODULES

Power, voltage, and current parameters available in module datasheets are based on STC conditions, with a \( T_c \) standardized on 25ºC. However, crystalline PV modules vary electrical parameters especially according to the \( T_c \), which changes due to the solar radiation, air temperature and wind speed. So, (2) and (3) enable to calculate Open Circuit Voltage \( (V_{oc}) \) and Short Circuit Current \( (I_{sc}) \) according to \( T_c \) from Pinho et al. (2014). For these equations, \( \beta \) is Temperature Coefficient for \( V_{oc} \) and \( \alpha \) is the Temperature Coefficient for \( I_{sc} \).

\[
V_{oc}(T_c) = V_{oc}^{STC} \cdot \left(1 + \frac{\beta}{100} \cdot (T_c - 25)\right) \tag{2}
\]

\[
I_{sc}(T_c) = I_{sc}^{STC} \cdot \left(1 + \frac{\alpha}{100} \cdot (T_c - 25)\right) \tag{3}
\]

Related to the Maximum Power \( (P_{max}) \), to obtain the Maximum Power Voltage \( (V_{mp}) \) and Maximum Power Current \( (I_{mp}) \) according to the \( T_c \) variations, the coefficients can be substituted. So, the temperature coefficient for \( I_{mp} \) is almost identical to \( \alpha \) and the temperature coefficient for \( V_{mp} \) can be approximated to the Maximum Power Coefficient \( (\gamma) \) from Pinho et al. (2014). So, (4) and (5) enable to calculate \( V_{mp} \) and \( I_{mp} \) according to \( T_c \).

\[
V_{mp}(T_c) = V_{mp,STC} \cdot \left(1 + \frac{\gamma}{100} \cdot (T_c - 25)\right) \tag{4}
\]
\[ I_{mp}(T_c) = I_{mp,STC} \cdot \left(1 + \frac{\alpha}{100} \cdot (T_c - 25)\right) \] (5)

Thus, checking the effect of temperature on the voltage and current parameters in the modules is used in the electrical sizing of the PV systems to ensure a correct operation.

3.5 PV ARRAYS AND INVERTERS

Thus, some number (n) of PV modules connected in series form a string. In this sequence, according to Jäger et al. (2014), several modules arranged together under a single inclination and orientation and connected form an array. Thus, the strings from an array that are joined in the same MPPT make a parallel connection that follows the electrical conditions of (6) and (7) from Pinho et al. (2014).

\[ V_{array} = V_{string} = n_{modules} \cdot V_{module} \] (6)

\[ I_{array} = n_{strings} \cdot I_{string} = n_{strings} \cdot I_{module} \] (7)

According to the configurations recommended by the inverter manufacturer Fronius (2019), the system design was dimensioned using oversizing. Checking the voltage and current parameters provided by the PV arrays from Canadian Solar (2016), showed in Table 1, is necessary to ensure compatibility with the parameters supported by the inverters. In addition, the module manufacturer indicates that this type of module can only work on strings and arrays with voltage up to 1000 V.

<table>
<thead>
<tr>
<th>Table 1. PV module parameters.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td>( P_{max} )</td>
</tr>
<tr>
<td>( V_{oc} )</td>
</tr>
<tr>
<td>( V_{mp} )</td>
</tr>
<tr>
<td>( I_{sc} )</td>
</tr>
<tr>
<td>( I_{mp} )</td>
</tr>
<tr>
<td>( \alpha )</td>
</tr>
<tr>
<td>( \beta )</td>
</tr>
<tr>
<td>( \gamma )</td>
</tr>
</tbody>
</table>

Source: Adapted from Canadian Solar (2016).

The values of \( V_{oc}, V_{mp}, I_{sc} \) and \( I_{mp} \) were found for each PV array from parameters in Table 1 using (6) and (7). Then, the \( T_c \) influence in these values were calculated with
(2), (3), (4) and (5), using maximum and minimum temperatures for system location. The results are shown in Table 2.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Array A</th>
<th>Array B</th>
<th>Array C</th>
<th>Array D</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. modules</td>
<td>5x18</td>
<td>5x20</td>
<td>5x19</td>
<td>5x18</td>
</tr>
<tr>
<td>$P_{\text{max}}$</td>
<td>29.7</td>
<td>33.0</td>
<td>31.35</td>
<td>29.7</td>
</tr>
<tr>
<td>$V_{\text{oc}}$</td>
<td>820.8</td>
<td>912.0</td>
<td>866.4</td>
<td>820.8</td>
</tr>
<tr>
<td>$V_{\text{oc,10^\circ C}}$</td>
<td>859.0</td>
<td>954.4</td>
<td>906.7</td>
<td>859.0</td>
</tr>
<tr>
<td>$V_{\text{mp}}$</td>
<td>669.6</td>
<td>744.0</td>
<td>706.8</td>
<td>669.6</td>
</tr>
<tr>
<td>$V_{\text{mp,10^\circ C}}$</td>
<td>710.8</td>
<td>789.8</td>
<td>750.3</td>
<td>710.8</td>
</tr>
<tr>
<td>$V_{\text{mp,55^\circ C}}$</td>
<td>587.2</td>
<td>652.5</td>
<td>619.9</td>
<td>587.2</td>
</tr>
<tr>
<td>$I_{\text{sc}}$</td>
<td>47.25</td>
<td>47.25</td>
<td>47.25</td>
<td>47.25</td>
</tr>
<tr>
<td>$I_{\text{sc,55^\circ C}}$</td>
<td>48.0</td>
<td>48.0</td>
<td>48.0</td>
<td>48.0</td>
</tr>
<tr>
<td>$I_{\text{mp}}$</td>
<td>44.4</td>
<td>44.4</td>
<td>44.4</td>
<td>44.4</td>
</tr>
<tr>
<td>$I_{\text{mp,55^\circ C}}$</td>
<td>45.1</td>
<td>45.1</td>
<td>45.1</td>
<td>45.1</td>
</tr>
</tbody>
</table>

Source: the author (2020).

Thus, the next step is to check this data with the limit parameters of the inverter used, as seen in Figure 5. It is observed for the temperature of 10$^\circ$C, the voltage values are higher and for the temperature of 55$^\circ$C, the voltage values are lower. The values of all arrays must be contained within these limits for the PV system to function properly. Table 3 shows the inverter characteristics from Fronius ECO 25.0-3-S datasheet. The inverter Maximum Input Power ($P_{\text{in}}$) and the Maximum Input Current ($I_{\text{in}}$) are also shown.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{in, max}}$</td>
<td>37.57</td>
<td>kW</td>
</tr>
<tr>
<td>$V_{\text{oc, max}}$</td>
<td>1000</td>
<td>V</td>
</tr>
<tr>
<td>$V_{\text{mp, max}}$</td>
<td>850</td>
<td>V</td>
</tr>
<tr>
<td>$V_{\text{mp, min}}$</td>
<td>580</td>
<td>V</td>
</tr>
<tr>
<td>$I_{\text{sc, max}}$</td>
<td>66.3</td>
<td>A</td>
</tr>
<tr>
<td>$I_{\text{in}}$</td>
<td>44.2</td>
<td>A</td>
</tr>
</tbody>
</table>

Source: Fronius (2020).
According to data from Tables 2 and 3, values of $V_{oc}$ at 10°C were all below the maximum of 1000V. Both values of $V_{mp}$ at 10°C and at 55°C of all arrays were within the inverter $V_{mp}$ range from 580V to 850V. Values of $I_{sc}$ at 55°C were below the limit of 66.3A and values of $I_{mp}$ at 55°C were below the limit of 44.2A.

3.6 ENERGY PROJECTION

A simulation was performed for the proposed system to estimate productivity according to the layout of the PV array. The irradiation and the PV productivity data from Nova Cantu city was collected in Atlas Solar Paraná (Tiepolo et al., 2017), which has an updated database for this city. This data was processed in the Radiasol software by UFRGS (2020) to obtain the Generation Performance Rate (GPR) according to the orientation and inclination of the photovoltaic arrangement in that location. The GPR for the optimal case and for each PV array are shown in Table 4.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Optimal</th>
<th>Array A</th>
<th>Array B</th>
<th>Array C</th>
<th>Array D</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclination</td>
<td>24</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>º</td>
</tr>
<tr>
<td>Azimuth</td>
<td>0</td>
<td>320</td>
<td>180</td>
<td>320</td>
<td>320</td>
<td>º</td>
</tr>
<tr>
<td>GPR</td>
<td>100</td>
<td>97.3</td>
<td>91.8</td>
<td>97.3</td>
<td>97.3</td>
<td>%</td>
</tr>
</tbody>
</table>

Source: UFRGS (2020).

Then, the PV Monthly Energy Production ($E_{PV}$) in KWh per month was found with (8) from Tiepolo et al. (2017), based in the sum of the amounts of each array connected to an inverter MPPT. Each array production is the product of Installed Photovoltaic Rated Power ($P_{PV}$) in KWp, by the Daily Photovoltaic Productivity (Prod), by the Number of Days in the Month ($d_m$), by the GPR converted. So, it resulted in the
PV productivity graph in the Figure 6. Therefore, the expected production was 165,599 KWh per year.

\[ E_{FV} = \sum \left( \frac{P_{FV} \cdot Prod \cdot d_m \cdot GPR}{100} \right) \]  

Figure 6. Monthly energy production estimative of the PV system.

4 HOMOLOGATION

4.1 ELECTRICAL CONNECTION AND PROTECTION

To connect the photovoltaic strings to the inverter, solar energy cables and MC4 connectors were used. The cables are made of flexible copper with double insulation for 1.8kV and with UV protection. The 4mm² section was chosen considering the Brazilian regulation NBR 5410 from ABNT (2004) and the specifications of the module manufacturer Canadian Solar (2016).

Inside the inverter, as seen in Figure 7, there were 15A rated fuses for the positive and negative conductors of each string, which were suitable for the strings used in the arrangements, with a maximum current of 9.45A each. It also had Class II modular SPD, for DC protection of the photovoltaic arrangement with easy replacement, and an integrated electronic disconnect switch, for disconnecting the strings from the inverter DC input (Fronius, 2020).
The AC output was protected with SPD and with a 200A three-phase circuit breakers, both arranged in an electrical panel, as seen in Figure 8. Two 380V-to-220V 75kVA three-phase autotransformers were used for each two inverters, to make the inverters output compatible with the 220V phase-to-phase network. An overplus of 30% was kept between the power of the transformers and the power sum of the inverters, so the system can work continuously close to its maximum power without overheating or having overvoltage. Following NBR 5410 from ABNT (2004) and leaving an overplus, 1kV cables with 35mm$^2$ were used on each 380V inverter AC output and with 70mm$^2$ were used on each 220V autotransformer AC output.

4.2 EQUIPMENT DISPOSAL

The PV modules were installed on the existing roofs, even reducing some of their productivity compared to the ideal positioning. However, modules reposition was not considered due to extra costs, structural weight excess and the possibility of extra shading.
As showed in Table 4, the A, C and D arrays were positioned under 320º orientation, in North orientation. Also, the B array was positioned with 140º of azimuth, facing South. The final layout can be seen in Figure 9.

Figure 9. PV arrays final disposal in the existing roof.

Source: the author (2020).

The inverters have IP67 protection against water and dust, but they were kept in a covered environment and fixed into a solid wall by manufacturer recommendation. It was kept a spacing higher than 10 cm between each inverter and 20 cm from the ceiling, to allow better ventilation. The AC protection boxes and transformers were placed close to the inverters, as showed in Figure 10.

Figure 10. Inverters, transformers, and CA protection boxes final disposal.

Source: the author (2020).
4.3 PROJECT DOCUMENTS FOR APPROVAL

The permission for connecting the PV system to the grid required some project documents, which were prepared and inserted in COPEL's Electric Web Project (PEW) platform (COPEL, 2021).

Access request: The generation power considered was 100kW from inverters total power. So, the distributed mini-generation form was used, filling with information about the electric consumer unit characteristics and about the basics of the PV system.

Annotation of Technical Responsibility: The work dealt with an electrical engineering project, so this document brings civil liability to the engineer. The work type inserted was 'Energy Generation', based on 'Alternative Energies (Solar/Wind/etc)', with technical activity in 'Project', 'Execution', 'Installation Services' and 'Inspections'.

Implementation and expansion schedule: It was elaborated with the stages of the project’s design and execution in chronological expected dates. It was useful for inspection prepare, especially in cases involving network adjustments.

Electrical project descriptive memorial: It included detailed information about: the electrical data of the electrical unit such as location, consumption class, nominal voltage, circuit breaker and existing transformer; the installed photovoltaic solar energy system, the manufacturer, model, quantity and power of the photovoltaic modules and inverters; the arrangement characteristics of the PV arrays and inverters; the cables and protections dimensioning for CC and AC; the system’s grounding characteristics; the method and material for fixing the photovoltaic modules to the existing roof.

Blocks and Single-line diagrams: The Blocks diagram showed in a simplified way each item and protection used in the electrical project, omitting wiring phases and sections. The Single-line diagram was very detailed about the electrical input, the AC protection, AC wiring and auto-transformers, the PV arrays, DC wiring and inverters, all can be seen in Figures 11, 12 and 13.

Data for plant registration at ANEEL: COPEL collected some information to send to ANEEL. A spreadsheet was filled with data from the consumer unit and from the PV system.

Environmental license: The Environmental Institute of Paraná did not require an environmental license to this PV system due to its module implementation on the existing roofs, which has very low environmental impact.

Inverter Certification: In this case, the international certificate of conformity for the Fronius Eco 25.0-3-S inverter was sent with the project approval documents.
Figure 11. Single-line diagram with electric unit input.

Source: the author (2020).

Figure 12. Single-line diagram with AC protection and transformer.

Source: the author (2020).

Fig. 13. Single-line diagram with inverter and their PV arrays.

Source: the author (2020).
4.4 COPEL INSPECTION

Before requesting an inspection, some items from the existing electrical installation and the entrance pattern of the property were revised and corrected, trying to fulfil the regulations requirements. A warning plate containing the words 'Caution COPEL Distributed Generation' was fixed in the front of the electrical input standard, as seen in Figure 14, made of metallic materials.

![Warning plate for distributed generation.](image)

Source: the author (2020).

After project approval, the inspection was requested. It was performed by COPEL technicians following a specific checklist. There was a visual check of the energy generating system, the meter was upgraded to bidirectional mode and the CTs were checked. A test was carried out to check if the voltages did not rise too much with the inverters connected, operating under considerable power. To guarantee the correct disconnection of the generator system, the anti-island test was performed by turning off the general circuit breaker, checking if the inverters were disconnected from the grid and if there was no voltage in the phases.

5 SYSTEM OPERATION
5.1 SYSTEM DATA COLLECTION

One of the inverters had a datalogger, which is a data acquisition device which communicates with Fronius Solar Web server. Communication between the inverters was made by with 4-pair network cable using the master and slave configuration. The datalogger was connected to the internet via network cable. The inverters have sensors used to monitor energy production. These data are displayed in graphs or numerical values on the website. Alerts are also shown in case of errors.
The monitoring records every 5 minutes a history of information containing: AC current of each phase, DC current of each input, AC voltage of each phase, DC voltage of each input, power factor, total power, and apparent power. Fronius Solar Web recorded power generation values but not consumption values. Therefore, the AVA system from COPEL (2021) had consumption information for the consumer unit.

5.2 GENERATION DETAILS

The energy generated by the GD photovoltaic system is first consumed in the property's loads and the rest is sent to the COPEL’s network. So, the bidirectional meter marked how much energy was left over from generation and sent to the grid (Dantas; Pompermayer, 2018). Also recording how much was get back during times of high consumption or low production. Therefore, the total generation and the electrical characteristics records were available on inverter’s monitoring Fronius Solar Web server.

![Figure 17. Inverter Power and DC Voltage in a sunny day.](source)

On a sunny day, the DC voltage of PV arrays grew spontaneously when sun came up, but it operated close to 550V due to PV maximum power characteristics, as seen in Figure 17. This voltage fluctuated by several factors such as partial shading or clouds, affecting system performance. With higher solar radiation, the modules temperature increased and, consequently, the DC voltage decreased reasonably. The PV components temperature remained stable during full operation on a sunny summer day. Under maximum temperatures, the circuit breakers operated at 56°C, the inverters at 50°C, the autotransformers at 63°C. There were no heating points either in wiring or protections.
5.3 PRODUCTION AND BILLING SUMMARY FOR THE CONSIDERED PERIOD

The first three months of production and billing were analyzed. The PV system was activated in the late afternoon of September 20, 2019, by COPEL. It was observed that the beginning of the system's operation almost coincided with the day of COPEL's reading. The billing period was different from the monthly production period shown by system monitoring. It was possible to calculate how much energy was consumed immediately by the internal loads and the total energy consumed by the property. Thus, Table 5 shows a summary of the energy generated and used in the property in this period. There were no energy credits for later months and the local instantly consumption was, on average, 78% of the total produced.

Table 5 Energy summary for considered period in 2020.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Start Reading</td>
<td>Sep 21</td>
<td>Oct 21</td>
<td>Nov 21</td>
<td></td>
</tr>
<tr>
<td>End Reading</td>
<td>Oct 21</td>
<td>Nov 21</td>
<td>Dec 21</td>
<td></td>
</tr>
<tr>
<td>Total Production</td>
<td>16,143</td>
<td>17,195</td>
<td>16,115</td>
<td>KWh</td>
</tr>
<tr>
<td>Energy Sent</td>
<td>-3,604</td>
<td>-3,806</td>
<td>-3,148</td>
<td>KWh</td>
</tr>
<tr>
<td>Instantly Consumed</td>
<td>12,539</td>
<td>13,389</td>
<td>12,967</td>
<td>KWh</td>
</tr>
<tr>
<td>Surplus Charged</td>
<td>5,845</td>
<td>5,538</td>
<td>8,182</td>
<td>KWh</td>
</tr>
<tr>
<td>Compensated</td>
<td>+3,604</td>
<td>+3,806</td>
<td>+3,148</td>
<td>KWh</td>
</tr>
<tr>
<td>Total Received</td>
<td>9,449</td>
<td>9,344</td>
<td>11,330</td>
<td>KWh</td>
</tr>
<tr>
<td>Total Consumed</td>
<td>21,988</td>
<td>22,733</td>
<td>24,297</td>
<td>KWh</td>
</tr>
</tbody>
</table>

Source: COPEL (2021); Solarweb (2020).

Paraná state underwent on a partial exemption for the tax called ICMS and was charged only its portion of use of the electric lines for all energy sent and took back. Tariff flags were charged on excess consumption, but tariff flags on injected and compensated energy by renewable source were exempt. There was savings in reducing power demand use around R$250.00, by the generator system power support. Another factor observed was the reactive energy billed monthly, if corrected, can bring savings around R$700.00. The billed items were summarized in the items in Table 6.

Table 6. Billing summary for considered period.

<table>
<thead>
<tr>
<th>Reference</th>
<th>October</th>
<th>November</th>
<th>December</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Demand</td>
<td>R$1,828.04</td>
<td>R$1,810.79</td>
<td>R$ 1,994.08</td>
</tr>
<tr>
<td>Peak Energy</td>
<td>R$1,977.58</td>
<td>R$2,527.48</td>
<td>R$ 2,268.83</td>
</tr>
<tr>
<td>Surplus Off-peak</td>
<td>R$3,047.24</td>
<td>R$2,871.64</td>
<td>R$ 4,244.49</td>
</tr>
<tr>
<td>Reactive Power</td>
<td>R$699.49</td>
<td>R$ 718.76</td>
<td>R$ 814.56</td>
</tr>
<tr>
<td>Unreturned Flags</td>
<td>R$225.99</td>
<td>R$ 329.62</td>
<td>R$ 314.98</td>
</tr>
</tbody>
</table>

The total generation was greater than the minimum value estimated, as seen in the Figure 18, showing agreement for PV system productivity. Without the electricity generation, energy bills could reach an average of R$16,100.00 in this period, reaching the expected compensation.

Figure 18. Comparison between the minimum estimated and the real generated of the PV system for considered period.

<table>
<thead>
<tr>
<th>Energy Tax</th>
<th>R$117.45</th>
<th>R$ 124.04</th>
<th>R$102.59</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>R$7.895.79</td>
<td>R$ 8.382.33</td>
<td>R$9.739.53</td>
</tr>
</tbody>
</table>

Source: COPEL (2021)

6 CONCLUSIONS

The success in COPEL’s inspection guaranteed the effectiveness of this photovoltaic system and, therefore, reaching the main objective of this study. The DC dimensioning of the photovoltaic arrays, considering the variation with the temperature, ensured that the voltage and current parameters are within the limits of the inverter. The AC dimensioning was also successful, as no overvoltage or temperature rise was detected in the AC wiring and devices during the system's operation.

The estimate found is a minimum production value for conference. Atlas Solar Paraná and Radiasol software proved to be excellent free tools for productivity analysis of photovoltaic systems. They allowed calculating the monthly generation based on the actual inclination and orientation of the photovoltaic panels.

Distributed Mini-generation modality required many documents of the electrical project and a great effort during the homologation process, which were successfully
developed. However, environmental licensing documentation was not necessary because it was a roof placed PV system. Therefore, the inspection process occurred correctly since the possible adjustments or impediments were identified and previously resolved.

The system was working in accordance with productivity, operating temperature, and electrical characteristics. Through COPEL’s billing data and Fronius Solar Web's production monitoring, it was possible to understand and evaluate the performance of energy production. Therefore, the energy production and compensation proposed objective in this project has been achieved.
REFERENCES


