# DESEMPENHO ENERGÉTICO DA EXPANSÃO DA GERAÇÃO DISTRIBUÍDA EM INSTITUIÇÕES PÚBLICAS DE ENSINO SUPERIOR PÚBLICAS: ESTUDO DE CASO DO INSTITUTO FEDERAL DE EDUCAÇÃO, CIÊNCIA E TECNOLOGIA DO PIAUÍ, BRASIL

*Energy performance of distributed generation expansion in public higher education institutions: a case study of the Federal Institute of Education, Science, and Technology of Piauí, Brazil*

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**Resumo:** A Geração Distribuída nas Instituições Públicas de Ensino Superior sofreu grande expansão a partir de 2020, assim, este artigo tem por objetivo avaliar o desempenho energético dessa expansão. Para tanto, inicialmente, avaliou-se a inserção da geração distribuída no poder público e, utilizando-se como objeto de estudo o Instituto Federal de Educação, Ciência e Tecnologia do Piauí, caracterizou-se a expansão da Geração Distribuída dessas instituições, por meio de indicadores técnicos, econômicos e ambientais. Embora se tenha constatado o crescimento da potência de Geração Distribuída nesse setor, percebeu-se baixa representatividade desses sistemas na matriz de geração distribuída. A expansão mostrou-se viável e verificou-se a melhoria dos indicadores técnico-econômicos dos sistemas, o aumento da eficiência e da potência média dos inversores e módulos fotovoltaicos, além da simplificação dos arranjos. Entretanto, apenas metade dos sistemas inicialmente contratados foram comissionados e a instalação não respeitou critérios técnicos na escolha da localização e dos equipamentos, indicando-se que deve ocorrer a melhoria desses aspectos para a garantia da sua eficiência. Por fim, verificou-se que a expansão continua e que a metodologia utilizada se mostrou aplicável a outras instituições, fornecendo orientações para a contratação dos novos sistemas.

**Palavras-chave:** Sistema Fotovoltaico; Índices de Mérito; Poder público; Gestão energética.

**Abstract:** Distributed generation (DG) has experienced significant expansion in Brazilian public higher education institutions (HEIs) since 2020. Thus, this article aims to evaluate the energy performance of facilities involved in this scenario. Initially, the integration of DG into the public sector was assessed. Considering the Federal Institute of Education, Science, and Technology of Piauí (IFPI) as a case study, the expansion of DG is characterized through technical, economic, and environmental indicators. Although an increase is observed in DG capacity in this sector, there is a low representation of such systems in the DG energy mix. The expansion proved to be feasible, resulting in improved technical and economic indicators of the systems, increased efficiency and average power ratings of inverters and photovoltaic (PV) modules, as well as the simplification of arrangements. However, only half of the initially contracted systems were commissioned. The installation did not comply with technical criteria in the selection of location and equipment as well, thus denoting the need for improving such issues to ensure higher efficiency. Finally, it was found that the expansion continues to the date, whereas the used methodology was found to be applicable to other institutions, providing guidance for the procurement of new systems.

**Keywords:** Photovoltaic Systems; Figures of Merit; Public Institutions; Energy Management.

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# 1 INTRODUCTION

Universalizing access to reliable, renewable and affordable energy is one of the commitments of the global cooperation agreement undertaken by Brazil as a 2030 Agenda signatory. In this context, given the high levels of solar radiation in the country and, since the regulation of distributed generation in 2012, photovoltaic systems have been experiencing exponential growth, characterizing themselves as strategic in this context.

Approximately one quarter of the country's electricity is consumed by the commercial sector, which includes Higher Education Institutions (HEI). Characterized as non-residential buildings, these institutions experienced significant geographic expansion in the 1960s and, more recently, since 2007, Federal Higher Education Institutions have experienced significant expansion as a result of government programs that, above all, aimed at their restructuring and expansion.

As a result of this process, many of these institutions are now characterized as multi-campus organizations, with a large capilarity in the states, which enhances their role as a vehicle for social transformation. However, this new configuration requires actions that integrate environmental management and building infrastructure aiming their strategic objectives. Therefore, efforts must be made to continuously improve their manageable environmental aspects.

Energy use is one of these aspects and, like the rest of the country, there are already a large number of photovoltaic systems installed in these organizations, bringing economic, environmental and social benefits. However, given the viability of these systems in practically the entire national territory and the limited resources for the installation of new systems, this article aims to evaluating the energy performance of the expansion of Distributed Generation in public HEIs.

Therefore, the Federal Institute of Education, Science and Technology of Piauí was used as the object of study, a pioneer in the installation of Distributed Generation Systems in the state and which was also contemplated with the recent expansion of photovoltaic systems. Therefore, studies already developed at the institution were continued, and the conclusions presented may be relevant even to other types of organizations.

# 2 THEORETICAL BASIS

The utilization of solar energy, beyond natural processes, holds significant potential for sustainable development and positively contributes to the Agenda 2030, a global cooperation agreement published by the United Nations (UN) in September 2015. Member countries committed to 17 Sustainable Development Goals (SDGs) and 169 targets to be pursued over the subsequent 15 years (UN, 2015). Concerning energy utilization, under the seventh goal (affordable and clean energy), one aims to increase the share of renewable energy sources, which remains a persistent challenge. This is due to the rising demand driven by population growth and primarily by economic development, resulting in environmental impacts that can be mitigated through the expansion of renewable energy conversion systems at both national and global levels (EPE, 2023).

Traditionally, large amounts of electrical energy are generated far from consumption centers in power systems (centralized generation), thus demanding the use of transmission and distribution systems. This is because the current level of technological development requires electricity to be consumed as it is produced, given the challenge of storing it in large-size systems (Morais et al., 2021). However, in 2012, distributed generation (DG) was regulated in Brazil through a Regulatory Resolution issues by the Brazilian National Electric Energy Agency (ANEEL) (ANEEL, 2012), establishing a model wherein small electricity-generating systems (micro and mini systems) can be installed at consumer units. This allows the generated energy to be consumed by the user at the instant of generation, that is, involving simultaneous generation and consumption, with any surplus being injected into the distribution grid and accounted for as energy credits to be used in subsequent electricity billing (Costa et al., 2022).

Since the initial regulation, there has been an exponential growth in DG in Brazil (ANEEL, 2023; Costa et al., 2022). In 2021, a new federal law was enacted (BRASIL, 2021), establishing a new regulatory framework for DG. Although it provided legal certainty to the sector, it changes the rules regarding the tariffing of surplus electricity generated and injected into the utility power grid (generation credit). This change does not render the installation of new systems unfeasible but negatively impacts the resulting cash flow, further requiring the implementation of energy management systems (Sousa et al., 2023). In the context of electricity usage, DG in buildings, whether residential or commercial, becomes significant, as their electricity consumption accounts for 22.5% of the country's total consumption (EPE, 2023).

Higher education institutions (HEIs), categorized among non-residential buildings, underwent significant geographical expansion starting from the 1960s. This scenario demanded improved academic and administrative management to ensure unity and high performance across the newly configured multicampus organization (Zarantoneli; Paradela, 2020). In federal HEIs, this expansion became more pronounced after 2007 with the advent of the Support Program for the Restructuring and Expansion of Federal Universities (REUNI). All federal institutions joined the program from its inception year, experiencing a substantial increase in infrastructure (Zander et al., 2022). Furthermore, this expansion was greatly influenced by the establishment of Federal Institutes of Education, Science, and Technology (IFETs), which involved the implementation of new campuses and the restructuring of Federal Centers of Technological Education (CEFETs), Federal Agrotechnical Schools (EAFs), and Technical Schools affiliated to Brazilian Federal Universities. These institutions were brought on par with universities in terms of offering higher education programs and organizational structure (Rosinke et al., 2020; Carvalho et al., 2022).

Since energy usage is a manageable environmental aspect in HEIs, consolidating environmental management institutionalization is a must, considering this input as one of the managed environmental aspects (Silva et al., 2018; 2020). This enables these organizations to encourage concrete changes in social reality not only through their core activities but also through the integration of management and building infrastructure aiming to consolidate them as sustainable educational institutions. Brazil has a great potential for photovoltaic (PV) generation due to its vast territorial extension with solar irradiation rates higher than those of European countries that lead this scenario (Pereira et al., 2017). Furthermore, Silva et al. (2021) highlight the implementation of grid-connected PV systems (GCPVSs) in several Brazilian HEIs: Federal Technological University of Paraná (UTFPR), Federal University of Uberlândia (UFU), Federal Institute of Education, Science and Technology of Rio Grande do Norte (IFRN), Federal University of Piauí (UFPI), and Federal Institute of Education, Science and Technology of Piauí (IFPI). All facilities are characterized as micro and mini-generation systems, in which proper figures of merit demonstrate technical feasibility.

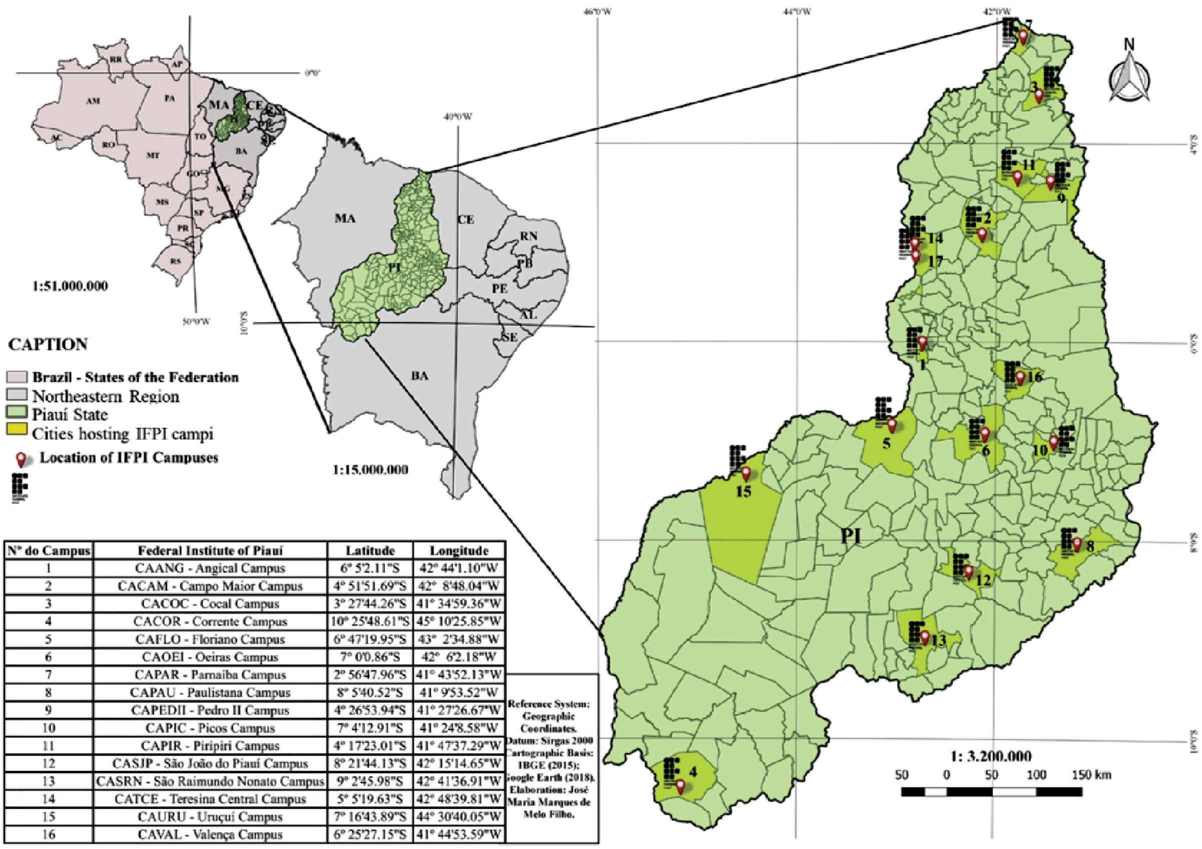
Still in this context, compared to the rest of Brazil, the Northeast region has the highest average irradiation and lowest interannual variability, which are mandatory characteristics for the implementation of PV systems. This behavior can also be observed in the state of Piauí, whose municipalities have a daily average solar irradiation 4% higher than the average of the Northeast region (Pereira et al., 2017). In November 2019, the Brazilian government released R$60 million for the installation of 852 PV plants in federal technological education institutions, which would yield estimated annual savings of R$17.7 million (BRASIL, 2019).

Most of the municipalities in Piauí with the highest generation potential are located in the southeast region of the state. The installation of PV systems is technically and economically viable, resulting in great strategic adherence. Potential benefits include reducing energy costs, preserving the environment, and the core activities of HEIs, given that the installation of PV systems can stimulate teaching, research, and extension activities (Silva et al., 2021). (Silva et al, 2021). Since the state of Piauí was also included in government programs, 10 new PV systems were commissioned at IFPI, with an average power of 47.5 kWp in the year 2020 (Silva et al., 2021). Furthermore, it is worth mentioning that this is follow-up research of (Morais et al., 2021) and (Silva et al., 2021). Overall, all aforementioned studies can contribute to regional development and the UN global agenda or sustainable development by encouraging the increased usage of renewable energy sources.

## 3 MATERIALS AND METHODS

Federal Institute of Education, Science and Technology of Piauí (IFPI) (Figure 1) was established in 1909 as the School of Artisan Apprentices of Piauí (EAAP). The internalization process began in 1986 with the construction of the Decentralized Teaching Unit (UNED) of Floriano (inaugurated in 1994) and underwent significant expansion, particularly from 2008 onwards, with the creation of the Federal Institutes of Education, Science, and Technology, with the creation of 12 new campuses and 3 new advanced campuses (Rêgo, 2015; IFPI, 2020). This expansion was the result of a national policy aimed at expanding and internalizing access to technological education (Pereira; Cruz, 2019; Rosinke et al., 2020; Carvalho et al., 2022), which led IFPI to consolidate itself with a multicampus organizational structure.

Figure 1 – Distribution of IFPI campuses




| Nº do Campus | Federal Institute of Piauí | Latitude | Longitude |
|---|---|---|---|
| 1 | CAANG - Angical Campus | 6° 5'2.11"S | 42° 44'1.10"W |
| 2 | CACAM - Campo Maior Campus | 4° 51'51.69"S | 42° 8'48.04"W |
| 3 | CACOC - Cocal Campus | 3° 27'44.26"S | 41° 34'59.36"W |
| 4 | CACOR - Corrente Campus | 10° 25'48.61"S | 45° 10'25.85"W |
| 5 | CAFLO - Floriano Campus | 6° 47'19.95"S | 43° 2'34.88"W |
| 6 | CAOEI - Oeiras Campus | 7° 0'0.86"S | 42° 6'2.18"W |
| 7 | CAPAR - Parnaíba Campus | 2° 56'47.96"S | 41° 43'52.13"W |
| 8 | CAPAU - Paulistana Campus | 8° 5'40.52"S | 41° 9'53.52"W |
| 9 | CAPEDII - Pedro II Campus | 4° 26'53.94"S | 41° 27'26.67"W |
| 10 | CAPIC - Picos Campus | 7° 4'12.91"S | 41° 24'8.58"W |
| 11 | CAPIR - Piripiri Campus | 4° 17'23.01"S | 41° 47'37.29"W |
| 12 | CASJP - São João do Piauí Campus | 8° 21'44.13"S | 42° 15'14.65"W |
| 13 | CASRN - São Raimundo Nonato Campus | 9° 2'45.98"S | 42° 41'36.91"W |
| 14 | CATCE - Teresina Central Campus | 5° 5'19.63"S | 42° 48'39.81"W |
| 15 | CAURU - Uruçuí Campus | 7° 16'43.89"S | 44° 30'40.05"W |
| 16 | CAVAL - Valença Campus | 6° 25'27.15"S | 41° 44'53.59"W |

Source: Silva et. (2018).

Since its establishment in 1909, its objectives have evolved, and in 2020, IFPI aimed to be "consolidated as a center of excellence in professional, scientific, and technological education, remaining among the best educational institutions in the country" (IFPI, 2020). The institution has 17 university campuses, as well as three advanced campuses and the rectorate head office, distributed in all regions of the state. Thus, all the buildings of the institution comprise the scope of the present research, and therefore, it is a census and deductive in nature.

IFPI, like other HEIs in the country, is regarded as an energy consumer of the public sector type by electrical utilities. Thus, according to the methodology used by Silva et al. (2023), data was initially collected from ANEEL (ANEEL, 2023) regarding the DG in Brazil, in the Northeast region, and specifically in the state of Piauí. This is necessary to assess the integration of this technology in these types of consumers, as well as the relevance of this particular HEI in this context. For this purpose, spreadsheets and data analysis tools were used (Microsoft, 2021; 2022).

Ultimately, given the confirmation of the existence of remote monitoring systems in all installed systems, the electricity generation in new PV systems installed at the institution was assessed in the first year after commissioning, as well as the electricity consumption in the year prior to commissioning

(Silva et al., 2020). The generation percentage in relation to consumption and figures merit for technical analysis such as the capacity factor, final productivity, and performance rate were calculated. The corresponding greenhouse gas emission rates not emitted into the atmosphere were also determined based on the emission levels of the country's energy matrix (Morais et al., 2021; Mesah et al., 2019). Analyzing the aforementioned parameters, it is possible to compare systems operating in different configurations and technologies, as well as in different regions (Nóbrega et al., 2018).

The capacity factor (CF) of a PV system is the ratio between the energy generated during a specific period and the rated power (Thotakura et al., 2020). It can be calculated from Eq. (1), where $P_0$ is the rated power of the PV system and $E$ is the electrical energy generated by the system during a given time interval ($t_2$ - $t_1$). This parameter allows for assessing the operating time of PV modules at full load condition (Qiu et al., 2022), providing information about the utilization of available solar resources, typically over a year, which consists of 365 days or 8760 hours (Mesah et al., 2019).

$$FC = \frac{E}{P_0\,(t_2 - t_1)} \tag{1}$$

In turn, the final productivity ($Y_f$), measured in kWh/kWp, is the ratio between the net energy produced and the peak power of the PV generator (Thotakura et al., 2020). This parameter should be calculated under standard test conditions (STC) from Eq. (2) (Zdyb; Gulkowski, 2020).

$$Y_f = \frac{E}{P_0} \tag{2}$$

According to Lagarde et al. (2021), there are losses related to the theoretical amount of generated energy and the actual output. Thus, Fuster-Palop et al. (2022) state that the performance ratio (PR) can be understood as an efficiency parameter that measures such energy losses associated with the ratio between the actual energy output $Y_f$ and the theoretical maximum energy output $Y_r$ during a same period as calculated from Eq. (3).

$$PR = \frac{Y_f}{Y_r} \tag{3}$$

According to Nóbrega et al. (2018), this parameter allows for comparing PV systems with different geographical locations, module positions, and rated powers, as it normalizes productivity in relation to solar irradiation, through the reference productivity $Y_r$. One can calculate the latter parameter from Eq. (4), which gives the ratio between the total irradiation on the array plane $H$ (given in kWh/m$^2$) and the reference irradiance $G_{ref}$ corresponding to 1000 W/m$^2$ at STC.

$$Y_r = \frac{H}{G_{STC}} \tag{4}$$

This index can also be referred to as the number of hours of full sun, as it represents the duration of time during which solar radiation is at the reference level (Morais et al., 2021). In this work, it has been determined based on the geographical coordinates of the systems and the azimuthal deviation and inclination of the PV modules using dedicated software (LABSOL, 2010; Zomer et al., 2023; Gomes et al., 2023). In all analyses, the contracted expansion was compared with the existing PV systems of the HEI in the first year of operation to normalize the results.

## 4 RESULTS AND DISCUSSION

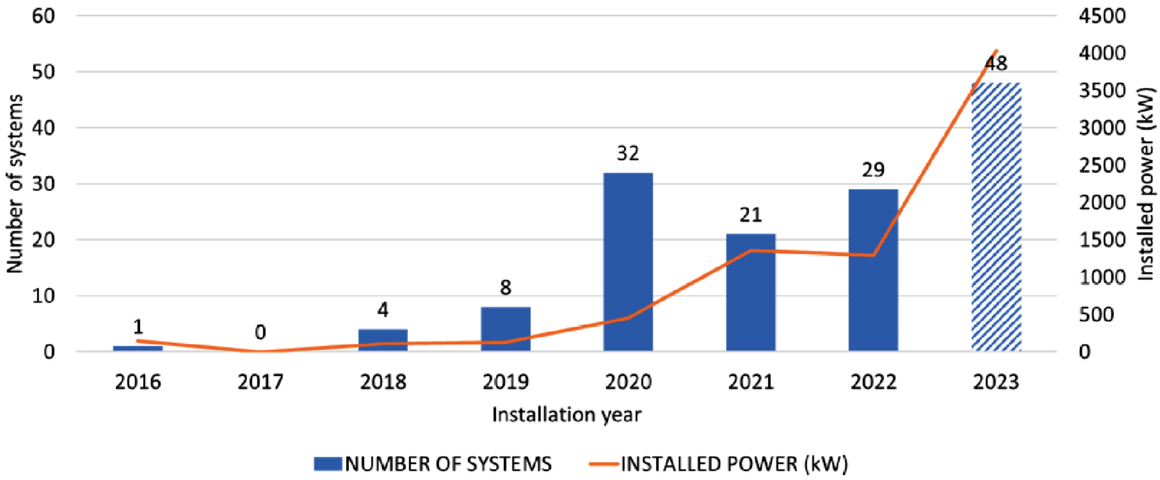
All DG systems in the state of Piauí are PV solar type. They account for a total installed power of 406,997.15 kW, corresponding to 8.85% of the installed power in the Northeast region of Brazil and 1.73% of the installed power in the entire country, with units classified according to the type of consumer (ANEEL, 2023). The PV system at the Floriano campus was the first mini-generation system installed, with a rated power greater than 75 kW and less than 5 MW) as well as the first system of a public organization installed in Piauí (ANEEL, 2023). After its installation in June 2016, there was an increase in installed power of 43.17% per year until the end of 2022, compared to an annual growth of

191.16% in the annual power increment of DG systems in Piauí (from 2015, the year of installation of the first system after the regulation of DG Generation in Brazil, until 2022).

As of September 9, 2023, there was a total of 143 DG systems corresponding to public consumer units in Piauí, with an average power of 52.56 kW per system, corresponding to 1.85% of the total DG installed power in the state (ANEEL, 2023). Consumer units of this type were responsible for 6.5% of the state's electricity consumption in the year 2022 (3,996 GWh) (EPE, 2023). Proportionally, this amount accounts for 2.5 times the installed capacity of DG systems in this sector. However, it is worth mentioning there is a greater relevance for public consumers in Piauí, as the representation of DG systems in public institutions is 37.36% and 58.27% higher compared to the Northeast region and the country, respectively.

The historical relevance of the public sector in the context of DG systems in Piauí has been low. However, there was an increase rate of 92.01% and 128.68% in the installed power and the number of systems, respectively, during the first eight months of 2023, accounting for the installation of 19 additional systems compared with the entire previous year and representing an increase of 111.86% as observed in Figure 2. Only 13 systems are characterized as mini-generation (systems with powers of up to 5 MW and greater than 75 kW), and 90.91% corresponds to micro-generation (systems with powers of up to 75 kW). Therefore, more than half of the DG systems in Piauí's public sector, that is, 51.05% are rated at less than 25 kW.

Figure 2 – Rated power and number of installed systems related to DG in the Piauí's public sector up to September 9, 2023




Source: prepared by the authors with data from ANEEL (2023).

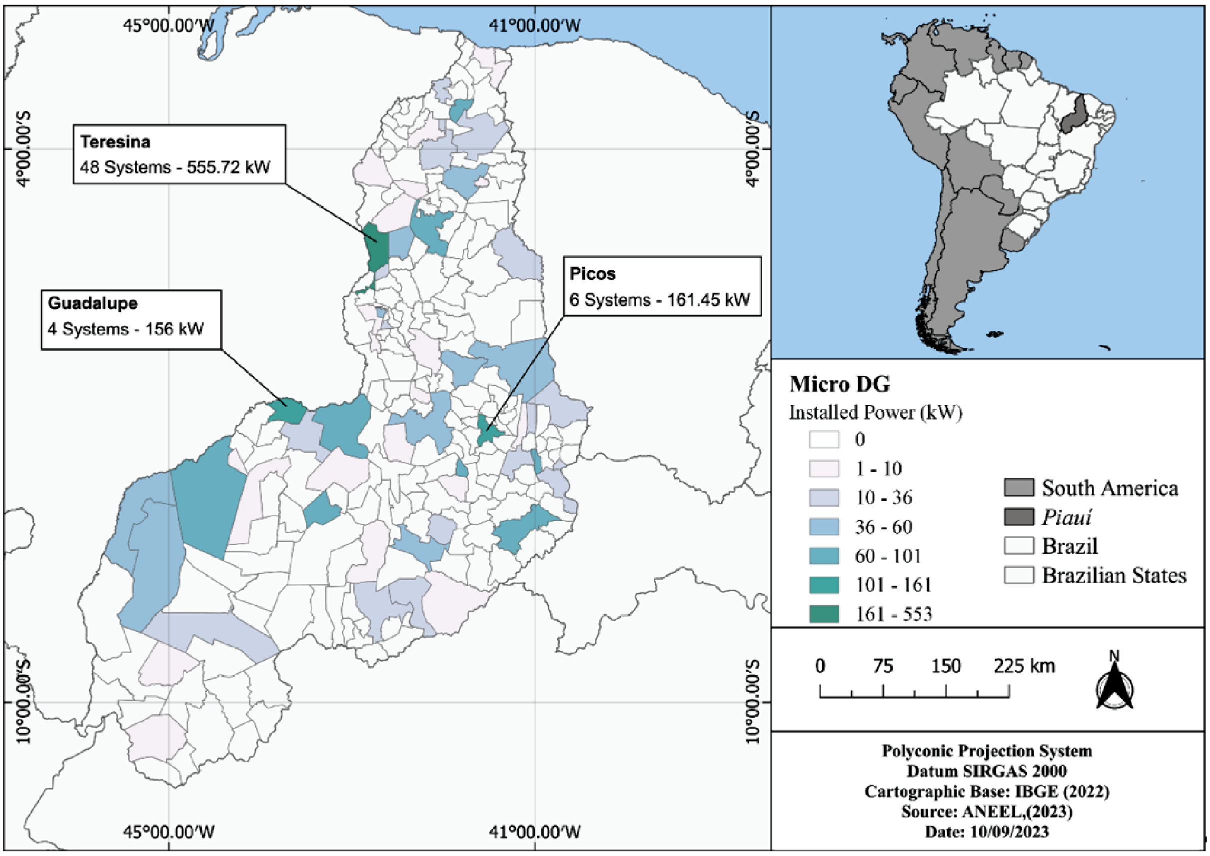
The city of Teresina, that is, Piauí's capital, has the highest number of DG systems in the public sector, corresponding to 54 installed systems (88.89% microgeneration), with a total power of 1686.72 kW (67.23% corresponding to minigeneration systems), with average powers of 11.52 kW and 189 kW for microgeneration and minigeneration system, respectively (ANEEL, 2023). The installation of micro DG systems in the public sector was identified in 55 municipalities, with a focus on Teresina (48 systems and 552.72 kW of total power), Picos (six systems and 161.45 kW of total power), and Guadalupe (four systems and 156 kW of total power), accounting for the first, second, and third highest positions in the installed power rank for this type of consumer (Figure 3). Regarding mini DG systems in the public sector, the municipalities of Coivaras (one system of 1,800 kW) and Altos (one system of 1,350 kW) are the first and second municipalities in terms of installed power, with the city of Teresina holding only the third position, with 1,134 kW, despite having six DG systems in the public sector (Figure 4).

These two large systems installed in the countryside of Piauí stem from a public-private partnership established by the state government (PIAUÍ, 2022). Therefore, they should be the subject of future studies, especially after the publication of the New Legal Framework for Distributed Generation, which established a new form of compensation for energy injected into the utility grid (BRASIL, 2022).

Furthermore, there is a significant presence of DG systems associated with the public sector in the capital. Owing to the large number of systems, Teresina holds the leading position among municipalities. However, small-scale systems predominantly characterize this scenario.

The DG system installed at the Floriano Campus (Figure 1), which is the first mini-generation system and the first public system in the state, has a rated power of 150 kWp. It consists of 660 polycrystalline modules arranged in the form of strings, which are sets of series-connected modules responsible for supplying an inverter. The strings, which are connected to seven inverters with an average power of 21.42 kW each, have a tilt angle of 15° and are oriented to the northeast (azimuthal deviation of 5°) and southwest (azimuthal deviation of –175°) (Morais et al., 2021). This system is technically feasible as demonstrate by a comprehensive analysis involving proper figures of merit. It aligns with the institution's mission and vision while bringing several benefits to teaching, research, and extension activities (Silva et al., 2021), especially owing to the high daily average irradiation rates of the city (5641 kWh/m²/day) (Pereira et al, 2017).

Figure 3 – Installed power of micro DG systems in Piaui's public sector per municipality up to September 9, 2023

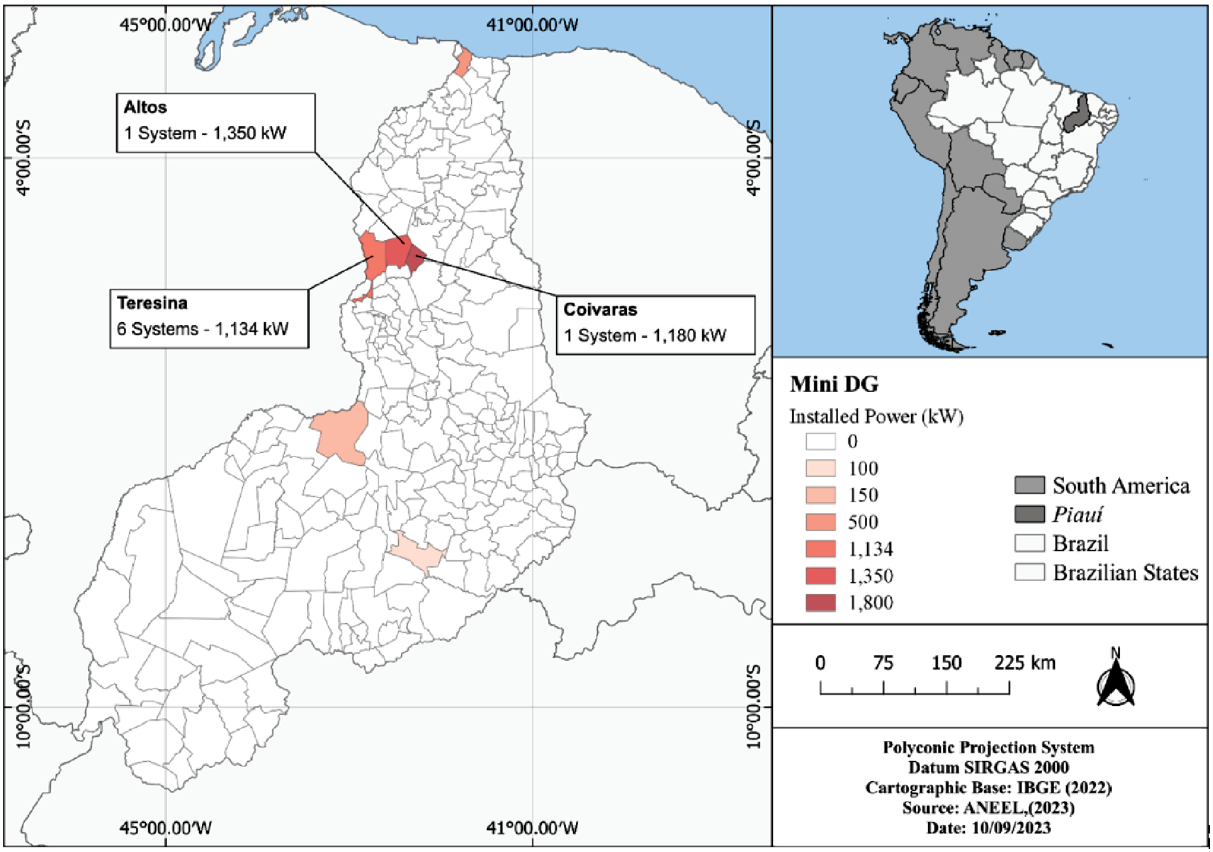



Source: prepared by the authors with data from ANEEL (2023).

However, even with all these benefits, its economic viability is called into question because of the high initial investment and high basic unit cost (BUC), low financial return, and long payback (Morais et al, 2019). In multicampus HEIs such as IFPI, the installation of small (microgeneration) systems in sites with a low technical-economic feasibility is better recommended to promote environmental education. Thus, higher investments should be directed to campuses with the highest technical, economic, and environmental benefits (Silva et al., 2021).

Moreover, in 2020, the commissioning of 10 new PV systems occurred: eight microgeneration systems with an average power of 53 kWp and two new minigeneration systems with rated powers 80 kWp and 119 kWp, totaling 625 kWp, with a similar BUC of R$3.06/Wp (Silva et al., 2021). However, a follow-up analysis carried out through a formal request to the engineering sector of the HEI identified that as of September 27, 2023, only five of the 10 new systems had been effectively installed, while the contract with the winning company of the bidding had been terminated: Central Teresina Campus (CATCE), South Teresina Campus (CTZS), Campo Maior Campus (CACAM), Valença Campus (CAVAL), and Paulistana Campus (CAPAU), adding 311.34 kWp of installed power (49.36% of the total contracted) and totaling R$934,138.10 in terms of initial investment (67% of the total contracted) (Table 1).

Figure 4 – Installed power of mini DG systems in Piaui's public sector per municipality up to September 9, 2023




Source: prepared by the authors with data from ANEEL (2023)

Table 1 – DG systems installed at IFPI on September 27, 2023

| Parameters | CAFLO | CTZS | CACAM | CAVAL | CAPAU | CATCE | Total |
|---|---|---|---|---|---|---|---|
| Initial Investment (R$) | 1,150,000.00 | 355,008.90 | 189,478.20 | 170,338.80 | 145,733.80 | 73,578.40 | 2,084,138.10 |
| Contracted Power (kWp) | 150.00 | 120.00 | 60.00 | 60.00 | 50.00 | 18.48 | 458.48 |
| BUC (R$/Wp) | 7.67 | 2.98 | 3.16 | 2.84 | 2.89 | 3.98 | 4.55 |
| Commissioning | 05/25/2016 | 09/03/2021 | 08/18/2020 | 10/21/2020 | 08/24/2020 | 06/10/2021 | NA |
| Monitoring | Yes | Yes | Yes | Yes | Yes | Yes | NA |

Source: prepared by the authors with data from (Morais et al., 2019) and (Silva et al., 2021).

From this analysis, it was observed that technical criteria were not decisive for the selection of campuses and the installation of PV systems, since units with higher availability of solar resources located in the southeastern region of the state were not chosen. However, the expansion of systems to various campuses of the HEI is noted. It can bring several benefits to the institution's core activity, in addition to reducing the BUC by 60.50%, even though the largest resources were not allocated to campuses where a higher BUC is expected, as found by Silva et al. (2021).

Furthermore, although all systems were contracted through a same bidding process and installed by the same company, except for the ones in the Floriano and Central Teresina Campuses, the PV systems are different, as it was possible to observe the use of modules from five different manufacturers according to Table 2. At the time of the survey, there were 1500 installed modules (840 new units since 2020), with average power and efficiency of 321.96 Wp and 18.20%, respectively. Comparing the new modules with those installed in 2016, the average power and efficiency increased by 42.55% and 19.60%, respectively.

Table 2 – PV modules installed at IFPI on September 27, 2023

| Manufacturer/Model | Campus | Type | Amount | Unit Power (Wp) | Total Power (Wp) | Efficiency (%) |
|---|---|---|---|---|---|---|
| CANADIAN SOLAR/CS6P-260P | CAFLO | Polycrystalline | 660 | 260 | 171,600 | 16.16 |
| JINKO SOLAR/JKM400M-72-H | CTZS | Monocrystalline | 300 | 400 | 120,000 | 19.88 |
| BYD/330 P6C-36 | CACAM/CAPAU | Polycrystalline | 342 | 330 | 112,860 | 18.30 |
| OSDA SOLAR/ODA400-36-M | CAVAL | Monocrystalline | 150 | 400 | 60,000 | 20.16 |
| JA SOLAR/JAM72S09-385/PR | CATCE | Monocrystalline | 48 | 385 | 18,480 | 19.30 |

Source: prepared by the authors with data from (Morais et al., 2019).

As for the inverters, there are 12 units from four different manufacturers, totaling a rated power of 425 kW, with an average efficiency of 98.52% (Table 3). Comparing the new systems with the one installed in 2016, there was an increase of 157% in average power and 0.38% in average efficiency. This is due the advent of commercial equipment with improved characteristics, leading to a reduction in the area occupied by PV systems, as well as the required materials and socio-environmental impacts.

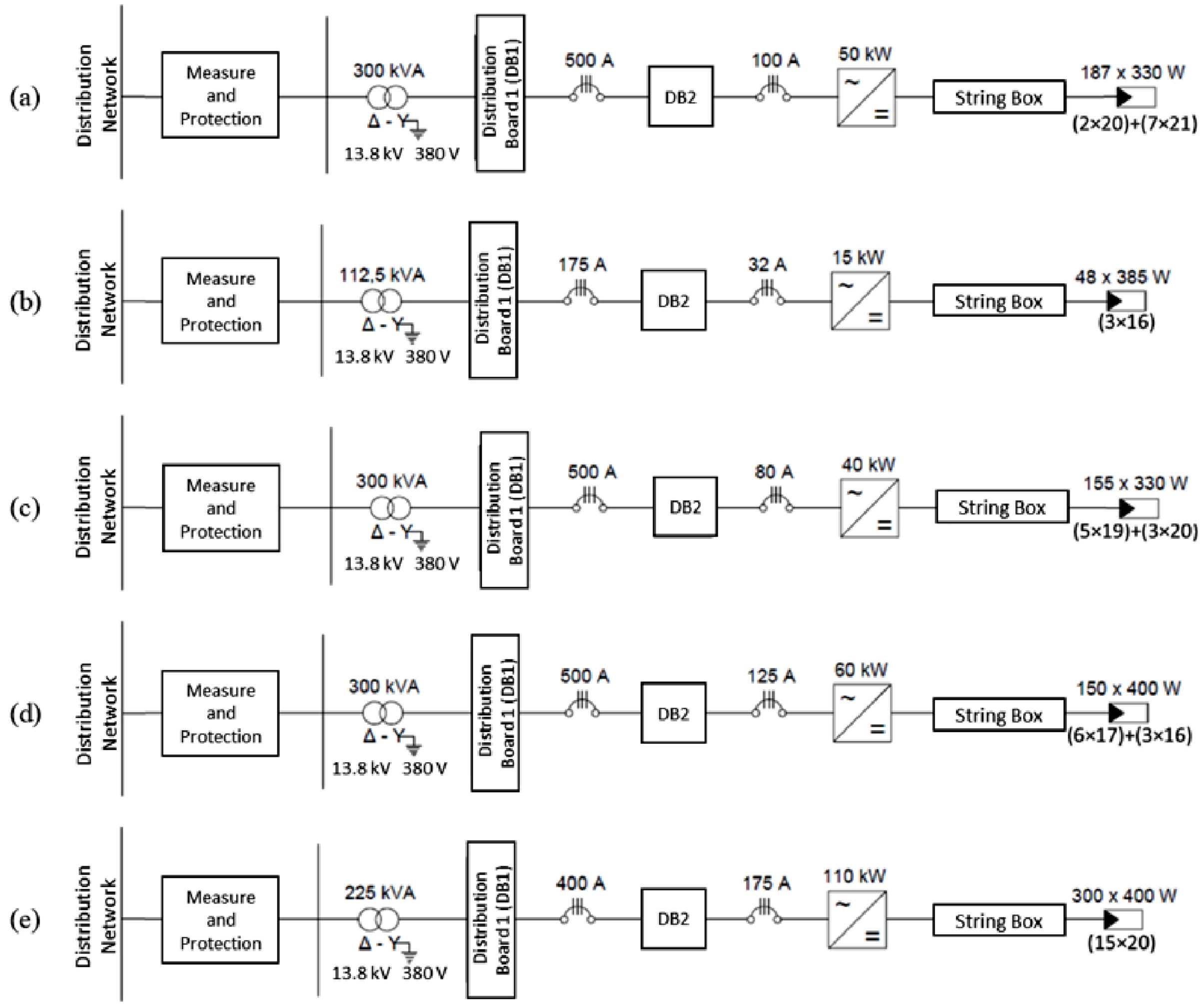
Table 3 – Inverters installed at IFPI on September 27, 2023

| Manufacturer/Model | Campus | Amount | Rated Power (W) | Total Power (W) | Efficiency | Type |
|---|---|---|---|---|---|---|
| SMA SUNNY/SIW500 ST010 | CAFLO | 1 | 10,000 | 10,000 | 98.1 | Three-phase/MPPT |
| SMA SUNNY/SIW500 ST015 | CAFLO | 1 | 15,000 | 15,000 | 98.2 | Three-phase/MPPT |
| SMA SUNNY/SIW500 ST025 | CAFLO | 5 | 25,000 | 125,000 | 98.3 | Three-phase/MPPT |
| SUNGROW/SG110CX | CTZS | 1 | 110,000 | 110,000 | 98.7 | Three-phase/MPPT |
| SUNGROW/SG50CX | CACAM | 1 | 50,000 | 50,000 | 98.4 | Three-phase/MPPT |
| DEYE/SUN-60 K-G | CAVAL | 1 | 60,000 | 60,000 | 98.9 | Three-phase/MPPT |
| SUNGROW/SG40CX | CAPAU | 1 | 40,000 | 40,000 | 98.6 | Three-phase/MPPT |
| GOODWE/GW 15KN-DT | CATCE | 1 | 15,000 | 15,000 | 98.3 | Three-phase/MPPT |

Source: prepared by the authors with data from (Morais et al., 2019).

Even though there is no defined standard for the systems, another advantage of using modern equipment lies in the possibility of achieving simpler arrangements compared to the diagram corresponding to the system installed at the Floriano Campus (Morais et al., 2021). A single inverter was used per project, even though the PV systems have multiple strings (Figure 5). The systems of the Campo Maior and Paulistana Campuses are installed on the main facade, the Central Teresina Campus is installed on the west facade of Building A, the South Teresina Campus is located on the north facade, and the Valença Campus is located on the southwest facade (Figure 6).

Figure 5 – Single-line diagrams of the PV systems installed at the Campo Maior Campus (a), Central Teresina Campus (b), Paulistana Campus (c), Valença Campus (d), and South Teresina Campus (e)




Source: prepared by the authors.

The Brazilian energy matrix emitted 78kg of $CO_2$ for each megawatt-hour of electricity generated in 2020. It is worth mentioning that $CO_2$ is a greenhouse gas that contributes to global warming, whose reduction is included in the goals of the Agenda 2030 (EPE, 2023). The PV systems installed at the HEI, which during their operation do not release greenhouse gases, generated 448,347 kWh in their first year of operation, equivalent to 2,784 Brazilian households in August 2023, while avoiding the emission of 34.97 tons of $CO_2$ into the atmosphere (EPE, 2023) (Table 4), thus contributing to reducing global warming in accordance with the UN Agenda 2030. However, despite all these benefits, some problems were identified in the operation, especially in the system installed at the Central Teresina Campus.

The system at the Central Teresina Campus was commissioned on June 10, 2021. However, despite the difficult access to the system due to its location, it was vandalized by criminals. By the end of 2022, electricity generation occurred in only eight out of 18 months, accounting for 44.44% of the total time, with a monthly average generation of 826.86 kWh. This represents only 0.69% and 1.43% of the energy consumption of the campus and the building where the system is installed, respectively (Table 4). Consequently, this resulted in significantly lower values for the performance metrics, with only 11.94% of the CR, final productivity, and PR compared to the average values of the other systems (Table 5).

Figure 6 – PV systems installed at the Campo Maior Campus (a), Central Teresina Campus (b), Paulistana Campus (c), Valença Campus (d), and South Teresina Campus (e)


Source: prepared by the authors.

Table 4 – New PV systems installed at IFPI in the first year of operation

| Campus | System Power (kWp) | Commissioning Date | Energy consumption in the year prior to installation (kWh) | Energy consumption in the year after installation (kWh) | Ratio between energy consumption and generation | Avoided $CO_2$ emissions (t) |
|---|---|---|---|---|---|---|
| CTZS | 171.60 | 09/03/2021 | 260,177 | 182,114 | 70.00% | 14.20 |
| CACAM | 120.00 | 08/18/2020 | 252,744 | 90,403 | 35.77% | 7.05 |
| CAVAL | 61.71 | 10/21/2020 | 151,109 | 85,955 | 56.88% | 6.70 |
| CAPAU | 60.00 | 08/24/2020 | 194,588 | 86,505 | 44.46% | 6.75 |
| CATCE | 51.15 | 06/10/2021 | 486,117 | 3370 | 0.69% | 0.26 |

Source: prepared by the authors.

Table 5 – Figures of merit of the PV system installed at IFPI in the first year of operation.

| Campus | System Power (kWp) | CF | Final Production (Wh/Wp) | Irradiation on the module plane (kWh/m²/day | Reference Production (Wh/Wp) | PR |
|---|---|---|---|---|---|---|
| CAFLO* | 171.60 | 17.04% | 1493.12 | 5.57 | 2033.05 | 73.54% |
| CTZS | 119.33 | 17.32% | 1517.62 | 5.72 | 2086.28 | 72.74% |
| CACAM | 60.00 | 16.72% | 1464.97 | 5.64 | 2058.30 | 71.17% |
| CAVAL | 60.00 | 16.35% | 1432.58 | 5.50 | 2007.20 | 71.37% |
| CAPAU | 50.50 | 19.31% | 1691.20 | 5.74 | 2095.40 | 80.71% |
| CATCE | 18.48 | 2.08% | 182.34 | 5.67 | 2067.73 | 8.82% |

Source: prepared by the authors with data from (Morais et al., 2019).
Nota: * Values determined based on (Morais et al., 2019).

Such conditions require both preventive and corrective maintenance by the HEI to fully restore the system and prevent future failures. However, a new PV system is currently being installed and commissioned on this campus. The initial investment for this system is R$ 950,000.00, with a rated power of 250 kWp. It comprises 332 modules rated at 560 W for Block A, totaling 185.92 kWp, and 116 modules rated at 560 W for Block B, totaling 64.96 kWp. This new system has the potential to address the aforementioned inconvenient issues. Additionally, for determining the operational performance of DG expansion, the system installed on this campus was excluded from the analysis due to the encountered problems, this being an outlier.

In this expansion, it is evident that energy generation in the first year after system installation accounted for over half of campus energy consumption in the previous year (51.8%). Notably, Campo Maior and Valença campuses had the lowest and highest percentage generation compared to consumption, corresponding to 35.8% and 70.0%, respectively. Additionally, considering the data regarding the installed modules and inverters in Tables 2 and 3, respectively, one can state that there was an improvement in the overall performance of the new systems. The CR and final productivity increased by 2.27% and 2.24%, respectively, with the PR increasing by 0.63% compared to the system installed at the Floriano Campus. Thus, encouraging the use of increasingly efficient equipment is essential for ensuring continuous improvement in system performance.

Finally, in addition to the new systems of the Central Teresina Campus, another system is also currently under implementation and commissioning in the Picos Campus, consisting of 120 modules rated at 560 W, totaling 67.2 kWp and an initial investment of R$ 254,600.00. Both systems should be the subject of future studies to evaluate their performance, especially owing to the new DG regulation that is likely to impact the technical and economic viability. This new regulation would require improved energy management actions, for instance, given that the old systems were not affected by changes in DG legislation (Silva et al, 2023).

## 5 CONCLUSION

All distributed generation systems in Piauí are of the solar PV type. The systems installed in the public sector account for 8.85% of the installed capacity in the northeastern region of Brazil and 1.73% of the installed capacity nationwide. IFPI, a multicampus higher education institution, led the way in Piauí's DG scenario by installing the state's first mini-generation energy system and the first system implemented within a public organization. The latter demonstrated strategic alignment, technical feasibility, and a debatable economic feasibility due to its long payback period and poor cost-benefit ratio. However, apart from its socio-environmental benefits, its implementation in the institution could also stimulate teaching, research, and extension activities, thus contributing to its core mission.

Since the installation of the initial DG system in the public sector, there has been an increase in the state's installed capacity until the end 2022. This growth has also been observed nationwide since the implementation of the second DG regulation. Until then, DG was incipient in Piauí. Regarding the installed capacity of DG mini-generation systems in the public sector, the municipalities of Teresina, Picos, and Guadalupe stand out in the state. As for the installed capacity of this type of consumer, the municipalities of Coivaras, Altos, and Teresina are notable. However, there is a low participation of such consumers in the DG scenario compared to the consumption percentage, which accounts for 2.5 times the installed capacity in Piaui's electric energy matrix.

In the context of IFPI, the expansion of PV systems proved technically and economically viable, with the first year of operation generating enough electricity to power 2,784 Brazilian households and avoiding the emission of 34.97 t of CO2 into the atmosphere. This contributes to the reduction of greenhouse gas emissions and aligns with the targets of the 2030 UN Agenda. Considering this favorable framework, 10 new PV systems were contracted, expanding DG systems into rural areas of the state, resulting in reduced costs and increased technical and economic feasibility. However, it is worth considering technical and economic criteria when selecting locations for installing new PV systems at HEIs.

Furthermore, despite the increase of 311.34 kWp in installed capacity, only half of the contracted systems were installed. The contract with the company hired for installation was terminated, with only 67% of the committed value invested, thus demanding greater caution in future bidding processes. Analyzing the seven-year period since the installation of IFPI's first system, it was also noted that these new systems demonstrated improvements in performance indices, including the efficiency and average power of the installed modules and inverters. This enhancement reflects the evolution of PV generation technology, leading to simplified arrangements and a consequent reduction in the systems' footprint, material usage, and socio-environmental impacts associated with distributed generation. These advancements should be continuously encouraged to further enhance the performance of DG systems.

However, a standard procedure was not followed in equipment selection, indicating the need for improved specifications in future contracts to ensure increased efficiency and ease of maintenance. Additionally, one of the analyzed systems was vandalized and remained inactive for more than half of the time, compromising operational performance. Therefore, implementing efficient energy management systems aligned with the maintenance sector of HEIs would be necessary to minimize these issues.

In summary, the expansion of the DG scenario in HEIs persists, as demonstrated by the contracting of two new systems for IFPI. These systems should be the focus of future studies, particularly in light of Brazil's New Legal Framework for DG. Aiming to contribute to sustainable regional development, the methodology used in this study for assessing the operational performance of PV systems can be applied to other organizations, provided that a monitoring system to measure energy generation and consumption exists.

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