

Expansion of photovoltaic systems in multicampi higher education institutions: evaluation and guidelines

Expansão de Sistemas Fotovoltaicos em Instituições de Ensino Superior Multicampi – Análise e orientações

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ABSTRACT

Considering the multicampi organizational structure of higher education institutions (HEIs), the expansion of photovoltaic (PV) systems previously installed in the facilities, the great potential for PV generation in Brazil, and the 2030 Agenda, the general goal of this research study is to evaluate and promote the expansion of the aforementioned PV systems. For this purpose, the PV system installed at the Federal Institute of Education, Science and Technology of Piauí comprising a future expansion is characterized by a thorough literature and documentary research. The solar resource available at the campuses of the institution was estimated using the second version of the Brazilian Atlas of Solar Energy. The technical-economic viability of the system expansion is assessed through the average parameters and minimum performance indexes required by the institution. Thus, it is possible to prove the effectiveness of the methodology to identify investment priorities and guide the construction and expansion of other PV systems, confirming that this process is technically and economically feasible as associated with strategic adherence, also bringing several environmental benefits.

Keywords: distributed generation; photovoltaic solar energy, renewable energy sources; solar atlas.

RESUMO

Considerando a estrutura organizacional multicampi de instituições de ensino superior e a recente expansão de sistemas fotovoltaicos instalados nessas organizações, além do grande potencial de geração fotovoltaica no Brasil e a Agenda 2030, este artigo tem o objetivo geral de avaliar e orientar a expansão desses sistemas nessas instituições. Para tanto, caracterizou-se o sistema fotovoltaico instalado e expansão contratada no Instituto Federal de Educação, Ciência e Tecnologia do Piauí com uma pesquisa bibliográfica e documental; estimou-se o recurso solar disponível aos seus campi utilizando-se a segunda versão do Atlas Brasileiro de Energia Solar; e verificou-se a viabilidade técnico-econômica da expansão dos sistemas com os parâmetros médios e índices mínimos de desempenho exigidos pela instituição. Por fim, pôde-se comprovar a eficácia da metodologia para identificar prioridades de investimento e orientar a construção e a ampliação de sistemas, comprovando-se que esta expansão é viável técnica-economicamente, com aderência estratégica, trazendo benefícios ambientais e à sua atividade fim.

PALAVRAS-CHAVE: Fontes Alternativas; Fontes Renováveis; Geração Distribuída; Atlas Solarimétrico.

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Introduction

Considering the need to grant universal access to energy, increase the share of renewable energy sources, double the global energy efficiency index, as well as strengthen international cooperation in research and technology transfer, the member countries of the United Nations (UN) committed to the seventh Sustainable Development Goal (SDG), namely, accessible and clean energy (UN, 2015a). This is a global cooperative planning and action program (Agenda 2030) composed of member countries, comprising 17 goals to be pursued in the subsequent 15 years (UN, 2015b).

The electric energy can be regarded as an infrastructure tool that promotes citizenship. However, the population growth, and especially the economic development, generates an increasing demand that must be met with high energy efficiency or the implementation of new energy generating plants, causing significant social and environmental impacts (Brasil, 2019b). As a consequence, the rapid depletion of conventional energy sources and the concern with environmental issues have driven the search for new, more efficient energy alternatives (Villela et al., 2017). Thus, renewable energy sources become relevant and indispensable for the development of a sustainable electricity generation system (Khan and Arsalan, 2016).

Renewable energy sources are currently used worldwide to reduce the impact of modern society on the environment (Goel and Sharma, 2017). Photovoltaic (PV) solar energy stands out as one of the most promising solutions, since it has nearly unlimited availability and accessibility throughout the planet and can be integrated into distinct types of buildings in the urban environment. Dávi et al. (2016) reported that the greenhouse gas emissions associated with this source are much lower than those of conventional fossil fuel-based electricity generation technologies. Most of the impacts of the PV systems are related to the production of cells (Silva, L.R. et al., 2018). Such impacts were assessed by Bezerra et al. (2018) who, when carrying out the life-cycle analysis of a PV module from the “cradle to the gate,” could verify the large amount of fossil fuels used in its production. Other harmful effects include the great impact on ecotoxicity, eutrophication of fresh water, and human toxicity, mainly due to the presence of heavy metals and other toxic substances in its composition.

In 2018, 11 countries installed more than 1 GW of PV facilities. Brazil and other 30 countries reached this cumulative capacity by adding a total of 103 GW worldwide, corresponding to an increase of 25.18% compared with the previous year, thus totaling 512 GW (2.9% of the world electricity matrix) (IEA, 2019). Even though it represents only 0.13% of the Brazilian energy matrix, the capacity of PV solar energy increased by 92.29% in 2019, reaching 1,798 MW. This is mainly due to the construction of large PV plants (centralized generation) and installation of grid-connected PV systems (GCPVSs) in consumer units (distributed generation) (Brasil, 2019a). Sommerfeldt and Madani (2016) stated that the increased use of such energy source is mainly observed in countries whose government policies created fa-

vorable economic conditions. In Brazil, the publication of normative resolution RN No. 482/2012 by the Brazilian National Electric Energy Agency (ANEEL), which standardized the inclusion of PV solar energy in the energy matrix through distributed micro- and mini-generation units, as well as its subsequent amendment RN No. 687/2015 of ANEEL (ANEEL, 2015), established conditions and incentives for consolidating the distributed generation in the forthcoming years.

Such regulatory actions associated with advances in PV technology, cost reduction, and subsidies were responsible for the significant increase in distributed generation in Brazil, mainly in the context of GCPVSs (Vale et al., 2017). Even with its significant role in the diversification of the Brazilian energy matrix, the increase in centralized generation is characterized by the need for new transmission and distribution lines that connect the plants to the load centers, as well as large areas needed for the implementation and operation of facilities, causing adverse socio-environmental impacts (Camargos et al., 2016). Thus, distributed generation becomes more advantageous from this perspective.

In turn, higher education institutions (HEIs) in Brazil experienced a significant expansion from the 1960s onward, thus requiring more efficient academic and administrative policies to ensure good performance in this new multicampi configuration (Nez, 2016). Recognizing this need, Silva et al. (2016) highlighted that consolidating the institutionalization of environmental management in universities is mandatory. It should be treated as a management model aiming at efficiency, efficacy, and effectiveness, which relies on economic and financial analyses and uses standardized procedures. Therefore, an environmental management system (EMS) is regarded as a continuous process and part of the management system of organizations. It is also used to develop and implement environmental policies that ensure acceptable management results on manageable environmental aspects, which include the use of energy.

Thus, the implementation of EMSs in HEIs should include energy management aspects, since the use of energy is the input quantity with the highest environmental risk index (Senna et al., 2014). HEIs should become an example of sustainability for the entire community, encouraging solid changes in the local reality not only through their core activity (teaching, research, and extension) but also through the articulation of management and building infrastructure to consolidate it as a sustainable space.

Brazil has a great potential for PV generation owing to its large territorial extension and solar irradiation levels higher than those of European countries, which are among the top PV generators (Pereira et al., 2017). Furthermore, Urbanetz Junior et al. (2014), Gomes et al. (2015), Buiatti et al. (2016), Morais et al. (2017), and Morais et al. (2019) highlighted the implementation of GCPVSs in several Brazilian HEIs, which include the Federal Technological University of Paraná (UFTPR), Federal University of Uberlândia (UFU), Federal Institute of Education, Science and Technology of Rio Grande in North (IFRN), Federal University of Piauí (UFPI), and Federal Institute of Education,

Science and Technology of Piauí (IFPI). The aforementioned facilities are characterized as micro- and mini-generation units, with good performance levels and proved technical feasibility.

In November 2019, the Brazilian government invested R\$60 million for the installation of 852 PV plants in federal technological education institutions, with estimated annual savings of R\$17.7 million (Brasil, 2019c). The savings can bring social and environmental benefits and applied in the core activities of HEIs. However, the feasibility of installing such systems may vary according to technical and economic factors associated with the installation sites, such as the solar irradiation levels and electricity tariffs, which can be determined by multi-criteria assessment (Azizkhani et al., 2016; Sagbansua and Balo, 2016; Ebrahimi et al., 2018). Thus, as a follow-up investigation of the studies developed by Silva, O.A.V. de O.L. da et al. (2018), and Silva (2020), the general goal of this article is to evaluate and guide the expansion process of PV systems in a multicampi HEI. For this purpose, the IFPI is adopted as a case study because it has a GCPVS installed in the insti-

tution (Sá et al., 2017; Morais et al., 2019). It is also worth mentioning that the PV facilities are currently under expansion (Brasil, 2019c).

Methodology

The IFPI is a Brazilian federal HEI created in 2008 by Federal Law No. 11892. It aims to “be consolidated as a center of excellence in professional and scientific education and technology, standing among the best educational institutions in the country” (IFPI, 2020). From the Support Program for Federal Universities Restructuring and Expansion Plans, which contributed to the increase in the number of cities that host campuses, the IFPI could expand itself with the installation of 12 new campuses in the past 10 years. Thus, it has been consolidated as a multicampi organizational structure (Silva et al., 2017).

The institution currently has 17 campuses, distributed in all regions of the state of Piauí (Figure 1). Morais et al. (2019) highlighted the existence of a 150-kWp system installed at the Floriano Campus. Besides, Silva et al. (2017) and de Silva, Moita Neto, and Lira (2021)

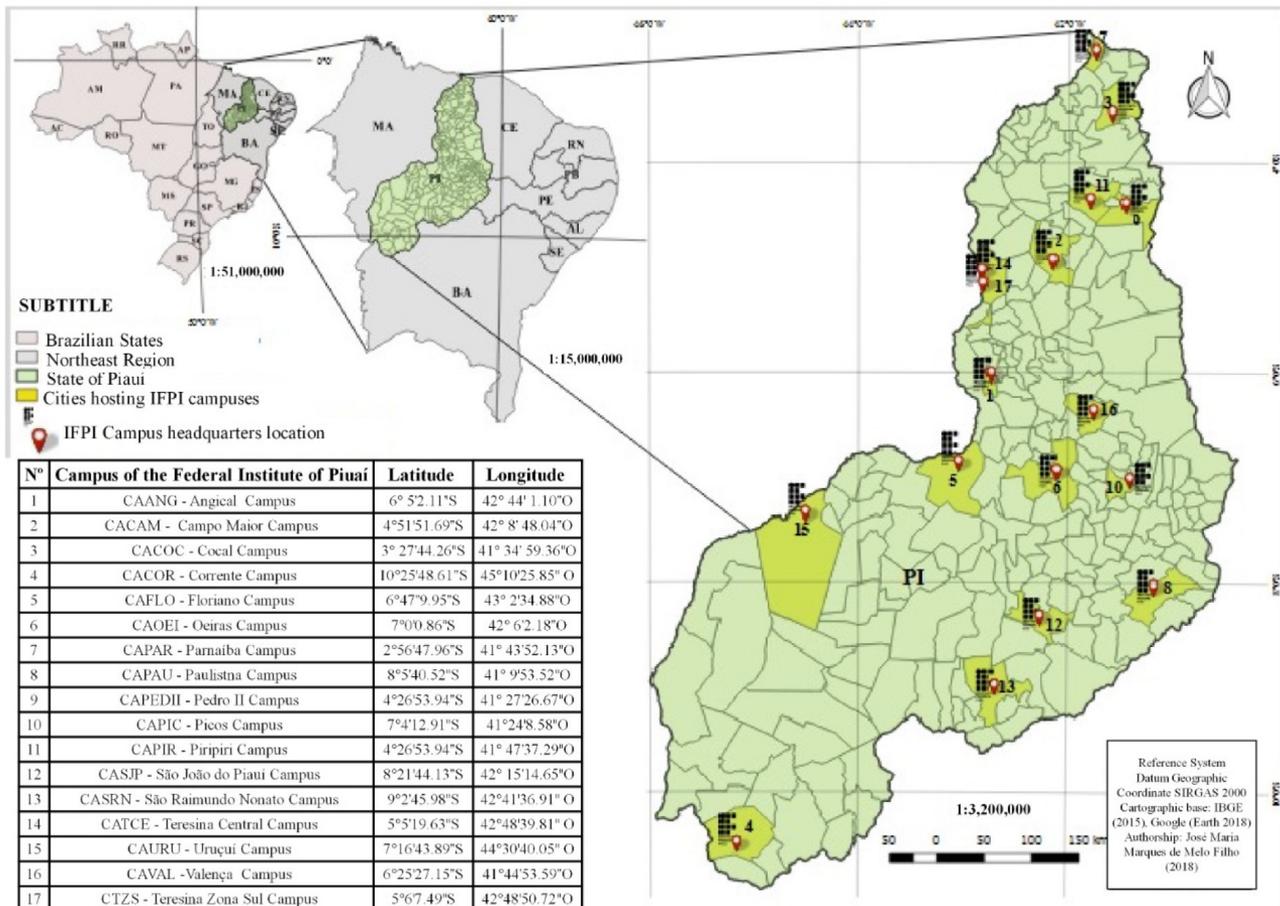


Figure 1 – Distribution of IFPI campuses. Source: Silva, O.A.V. de O.L. da (2018).

showed the need for investments in energy efficiency projects in the whole institution. Therefore, it is reasonable to state that all campuses are part of the scope of this research.

The study starts with the characterization of the GCPVS installed at the Floriano Campus from a thorough bibliographical research on the technical–economic and environmental performance associated with the reduction of carbon dioxide emissions. Then, an electronic price registration auction was carried out for the eventual installation of a microgeneration unit at the HEI (IFPI, 2018). This process can be regarded as a benchmark for the latter acquisition of GCPVSs in HEIs located at seven distinct states, namely, Bahia, Rondônia, Mato Grosso, Mato Grosso do Sul, Minas Gerais, Ceará, and Piauí, totaling 3,234 kWp, among which the IFPI is included (Brasil, 2019c).

Some available official documents were analyzed to study the expansion of PV systems in the institution, with special attention given to the Transparency Portal of the Brazilian Government (Brasil, 2020a). Specific information was also requested directly to the institution through the electronic citizen information service (E-SIC) (Brasil, 2020b). The purpose is to identify in which campuses the systems will be installed and their technical–economic characteristics, comparing them with the previously installed GCPVS (Morais et al., 2019).

With regard to the technical performance, the parameters commonly used for monitoring and analysis, i.e., the figures of merit are the final productivity (Y) given in kWh/kWp, defined as the ratio of the liquid power flow of the entire system (E) to the total peak power of PV modules (P_o) in Equation 1 (IEC, 1998); the average overall performance or performance ratio (PR), this being a dimensionless quantity that express the ratio between the final productivity (Y_f) and the reference productivity (Y_r), determined based on the rated parameters of the system components according to Equation 2 (IEC, 1998); and the capacity factor (CF), which is a dimensionless quantity representing the activity level of a generation system through the relationship between the energy effectively produced (E) and the expected production at the rated power P_o during the very same period (Δt) as defined in Equation 3 (Nakabayashi, 2015). However, only the results provided by the first index will be used in the analysis of the new systems contracted by the HEI since they are not yet installed.

$$Y = \frac{E}{P_o} \quad (1)$$

$$PR = \frac{Y_f}{Y_r} \quad (2)$$

$$CF = \frac{E}{P_o \times \Delta t} \quad (3)$$

It is necessary to assemble a measurement system for assessing the available solar resource and determining the performance of PV sys-

tems. The setup comprises calibrated reference modules placed on the same plane of the system or pyranometers installed together with the system (IEC, 1998). However, the installation of such equipment as required by official standards in all the campuses would make the study cost-prohibitive. Therefore, the authors used the database of the second version of the Brazilian Atlas of Solar Energy (Pereira et al., 2017), which also served as a reference for determining the irradiation levels in the studies by Carneiro et al. (2019), Deschamps and R  ther (2019), Ferreira et al. (2018), Morais et al. (2019), and Paim et al. (2019).

To determine the solar irradiation levels, the geographical coordinates of each of campus were obtained. The average value of the annual overall irradiation available in the metadata of the second edition of the Brazilian Atlas of Solar Energy (Pereira et al., 2017) at the reference point closest to each campus was then calculated using Equation 4. The distance (d , in km) between the reference point of the Atlas and each campus was determined based on the mean Earth radius ($r = 6,371$ km) in the respective latitudes ($lat1$ and $lat2$) and longitudes ($long1$ and $long2$) of the points, where “ $\cos^{-1} \theta$ ” is measured in radians (Santos and Oliveira, 2018).

$$D = R \times \cos^{-1} [\sin(lat1) \times \sin(lat2) + \cos(lat1) \times \cos(lat2) \times \cos(long1 - long2)] \quad (4)$$

One can determine the PV system productivity from Equation 1 using the irradiation data associated with each campus, the characterization of contracted systems, and the minimum parameters required for the systems as established in the bidding process. In such analysis of technical viability, the annual energy generation (E) resulting from the installation of the GCPVSs in the campus could be determined from Equation 5 and the result is divided by the estimated power for the PV modules. It is possible to calculate E from the annual irradiation at the place of installation of GCPVS (H), the surface area of the modules (A), the efficiency of the modules (η), and the number of modules (N) (Vilalva, 2015). This estimative was still multiplied by the maximum loss factor, considering the global losses established by the HEI depending on the losses inherent in the GCPVS (IFPI, 2018), which are mainly due to the PV modules and inverters (Teles et al., 2018). The same factor was still divided by the system power to estimate the total power of the PV modules (Mac  do and Zilles, 2007; P  rez-Higueras et al., 2018).

$$E = H \times A \times \eta \times N \quad (5)$$

As for the analysis of economic viability, the basic unit cost (BUC) was determined by dividing the system cost by the total power, as well as taking into account the capital inflow due to the energy produced by the GCPVS. Considering the average monthly energy costs of year 2019 for the installation site, one could estimate the potential annual cost reduction associated with electricity consumption, as well as the capital outflow due to the implementation, operation, and maintenance

of the system. In addition, typical metrics used in economic engineering were adopted, such as the net present value (NPV) in Equation 6, so that the difference between the capital inflow and outflow (A_n) in each of the periods (n) is incorporated into the decision-making process of the project. This analysis also considers its respective useful life (t) and the discount rate (r); the internal rate of return (IRR), which is the discount rate that makes the NPV equal to zero; the payback when the NPV becomes positive; and the benefit-to-cost ratio (BCR), this being the ratio between the NPVs of capital inflows and outflows (Silva et al., 2019).

$$VPL = \sum_{n=1}^t \frac{A_n}{(1+r)^n} \quad (6)$$

The metrics were calculated considering the maximum annual degradation rate of the estimated generation and its minimum useful life, which results from the loss of system efficiency, in addition to maintenance and operation costs of 1% of the initial investment impacting the cash flow every 10 years (Nakabayashi, 2015). The discount rate is considered the difference between the average tariff adjustments of the local utility during the past 10 years and the estimated values for the Special System for Settlement and Custody (Selic) rate indicated as a reference by ANEEL (2018) (Figure 2).

Similarly, the irradiation data of all campuses were used to create rankings of generation potential, reduction of carbon dioxide emissions, and economic benefits, once again taking into account the energy tariffs for the year 2019. The hypothetical installation of PV systems in all campuses was considered in terms of the average values assumed by the parameters of other systems recently contracted by the HEI (Brasil, 2020a) and with the minimum efficiency defined for the systems (IFPI, 2018). The potential for reducing carbon dioxide emissions was determined only during the useful life of the project based on

data from the Energy Research Company (EPE), which calculates this parameter annually as a function of the amount of energy generated in the country in kWh (Brasil, 2019a).

In addition to the aforementioned analysis involving absolute values, two scales were created for measuring the benefits related to energy consumption and electricity costs. Finally, just as for the systems already contracted, the economic analysis for this proposed expansion was carried out in six scenarios, as given in Table 1. The maximum, minimum, and average BUCs of the systems (excluding outliers) were considered according to the offers presented by the companies in the electronic price registration auction carried out by the HEI (IFPI, 2018), in addition to the best and the worst economic benefit according to the defined ranking.

Results and discussion

The Floriano Campus has a built area of 9,481.41 m² and is used by 80 professors, 62 members of the administrative staff, 39 outsourced workers, and a total of 1,300 students during the morning, afternoon, and night shifts. The GCPVS of this campus was the first mini-generation system installed in Piauí, with a rated power greater than 75 kW and less than 5 MW. It started operating in June 2016, with a monthly average generation of 21,333 kWh in the first year of operation, corresponding to 32.44% of the overall energy consumption, while avoiding the emission of 25.93 tons of CO₂ during the same period (Sá et al., 2017).

This system is composed of 660 polycrystalline PV modules rated at 260 Wp, model CS6P-260P by Canadian Solar. The inverters correspond to one model SIW500 ST010, one model SIW500 ST015, and five models SIW500 ST025 by SMA Sunny Tripower, which can process a peak power up to 150 kWp (Morais et al., 2019). The modules are mounted on a fixed metallic structure with an inclination of 15°,

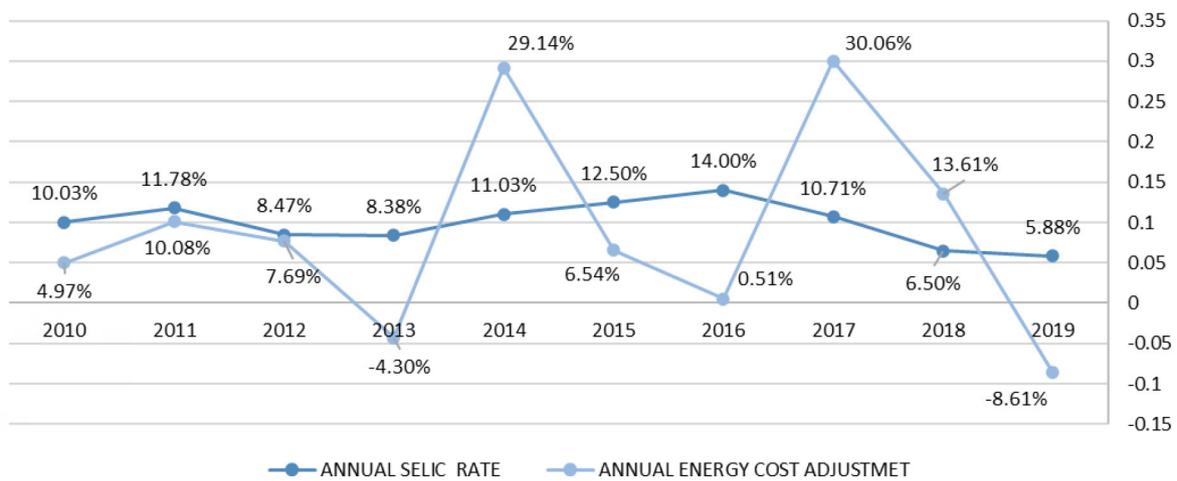


Figure 2 – Selic rate and tariff readjustment of the local energy utility from 2010 to 2019.
Source: Prepared by the authors using data obtained from Aneel (2020) and BCB (2020).

Table 1 – Scenarios for the economic analysis of the proposed expansion for the IFPI.

Scenarios	Initial investment	Economic benefits
1	Lowest BUC	Higher financial return
2	Average BUC	Higher financial return
3	Highest BUC	Higher financial return
4	Lowest BUC	Lower financial return
5	Average BUC	Lower financial return
6	Highest BUC	Lower financial return

oriented to the Northeast (azimuth deviation of 5°) on roofs 1, 2, 3, and 4N and to the Southwest (azimuth deviation of -175°) on roofs 4S and 5 (Figure 3).

The GCPVS has productivity, CF, and PR of 1,493.12 kWh/kWp, 17.04%, and 73.54%, respectively. It is reasonable to state that this is a technically viable project, especially considering that the aforementioned figures of merit assume higher values than those typically observed in other HEIs studied by Urbanetz Junior et al. (2014), Gomes et al. (2015), and Buiatti et al. (2016), mainly due to the high average daily irradiation levels of 5,641 kWh/m²/day. However, even with high strategic adherence, its economic viability is called into question considering the high initial investment (R\$ 1,150,000.00) and high BUC (R\$ 7.67/Wp), low financial return (cost-effectiveness ratio equal to 4.37), and high payback period (19 years after installation) (Morais et al., 2019).

This system motivated the creation of a subject entitled “renewable energy sources” in the Technical Course in Electromechanics, which is regularly offered by the institution. It also led to the implementation of the PV solar energy laboratory in the campus, as well as the development of a research project and three extension projects (Sá, 2019). In addition, two master’s dissertations (Morais, 2018; Sá, 2019) and one doctoral thesis (Silva, 2020) focused on the system were presented by professors from the institution, who also published some scientific articles. In addition to technical, economic, and environmental benefits, the PV system installed in the Floriano Campus brought significant advances with regard to teaching, research, and extension activities.

One could find the closest reference points of each of the 17 campuses in the database of the second version of the Brazilian Solar Energy Atlas (Pereira et al., 2017), considering their geographic coordinates in Figure 1 and using Equation 4. The distances between them are estimated based on the mean Earth radius, also identifying the annual average of daily global irradiation at each campus, as shown in Figure 4. Thus, it seems that most cities with the greatest potential for the installation of PV systems are located in the southeast region of the state.

One could then determine new sites for the installation of GCPVSs: eight microgeneration units with an average power of 53 kWp and two mini-generation systems whose peak powers are 80 and 119 kWp, to-



Figure 3 – Detailed view of the GCPVS installed at IFPI's Floriano Campus. Source: Morais et al. (2019).

taling 625 kWp with an average BUC of R\$ 3.06/Wp (Table 2) (Brasil, 2020a). However, even though it was contracted at the same time as the other systems, it should be noted that the Teresina Central Campus (CATCE) was assigned to other company than the other systems, with an average BUC 34% higher.

Except for CATCE, whose contract has not yet been consolidated by the HEI, the remaining systems were contracted through the electronic price registration system in the “turnkey” modality, this being a model that provides the material, installation, and commissioning for carrying out the project. The contract also includes a training course for operating the system, a 1-year maintenance period, and the monitoring system. The system must also meet minimum performance indices, with a maximum loss factor of 23%, among which the following ones stand out for PV modules: minimum rated power (260 Wp), minimum power per area unit (155 Wp/m²), minimum efficiency (15.89%), minimum service life (25 years), and maximum level of power degradation during the warranty period (10%) (IFPI, 2018).

Considering the average solar irradiation (Pereira et al., 2017) at the closest reference points to each of the campuses in Figure 4, all the aforementioned parameters were used in the technical-economic analysis of the contracted systems. A maintenance and operation cost corresponding to 1% of the initial investment is included, whereas the process is carried out every 10 years (Morais et al., 2019) (Table 2). The new contracted systems should result in a profit of R\$ 11,780,974.91 at the end of the useful life. They are also supposed to present technical-economic parameters superior to those of the system installed in 2016, with an estimated average productivity 15.63% higher and an average BUC 60.10% lower.

Table 2 – Technical–economic analysis of existing GCPVs already installed and contracted by IFPI from November 20, 2019 to April 20, 2020.

Campus	Total Power (kWp)	BUC (R\$/Wp)	Global Solar Irradiation (Wh/m ² ×day)	Estimated System Productivity (kWh/kWp)	NPV (R\$)	Payback (years)	IRR (%)	BCR
CAFLO*	150	7.67	5,641	1,506.21	263,172.06	19	1.91	4.37
CASRN**	60	2.84	5,894	1,700.80	1,148,063.20	3	36.31	0.15
CAPAU**	51	2.89	5,856	2,195.11	1,287,112.73	3	46.59	0.11
CACOR**	65	2.82	5,768	1,663.55	1,213,591.72	3	35.72	0.15
CACAM**	60	3.16	5,702	1,644.51	1,084,755.89	4	31.31	0.17
CAPEDII**	80	3.07	5,686	1,639.90	1,449,184.33	3	32.21	0.17
CAVAL**	60	2.84	5,683	1,639.03	1,099,972.87	3	34.92	0.15
CAPIR**	57	3.18	5,666	1,644.82	1,023,442.03	4	31.09	0.18
CATCE**	18	3.98	5,572	2,088.16	424,984.34	4	31.56	0.17
CTZS**	119	2.99	5,527	1,613.35	2,130,621.18	3	32.52	0.17
CAURU**	55	2.88	5,467	1,586.54	919,246.62	4	31.88	0.17
TOTAL**	625	-	-	-	11,780,974.91	-	-	-
AVERAGE**	62	3.06	5,682	1,741.58	1,178,097.49	3.40	34.41	0.16

*Existing system; **contracted systems. Source: Prepared by the authors using data from IFPI (2018), Morais et al. (2019), and Brasil (2020a).

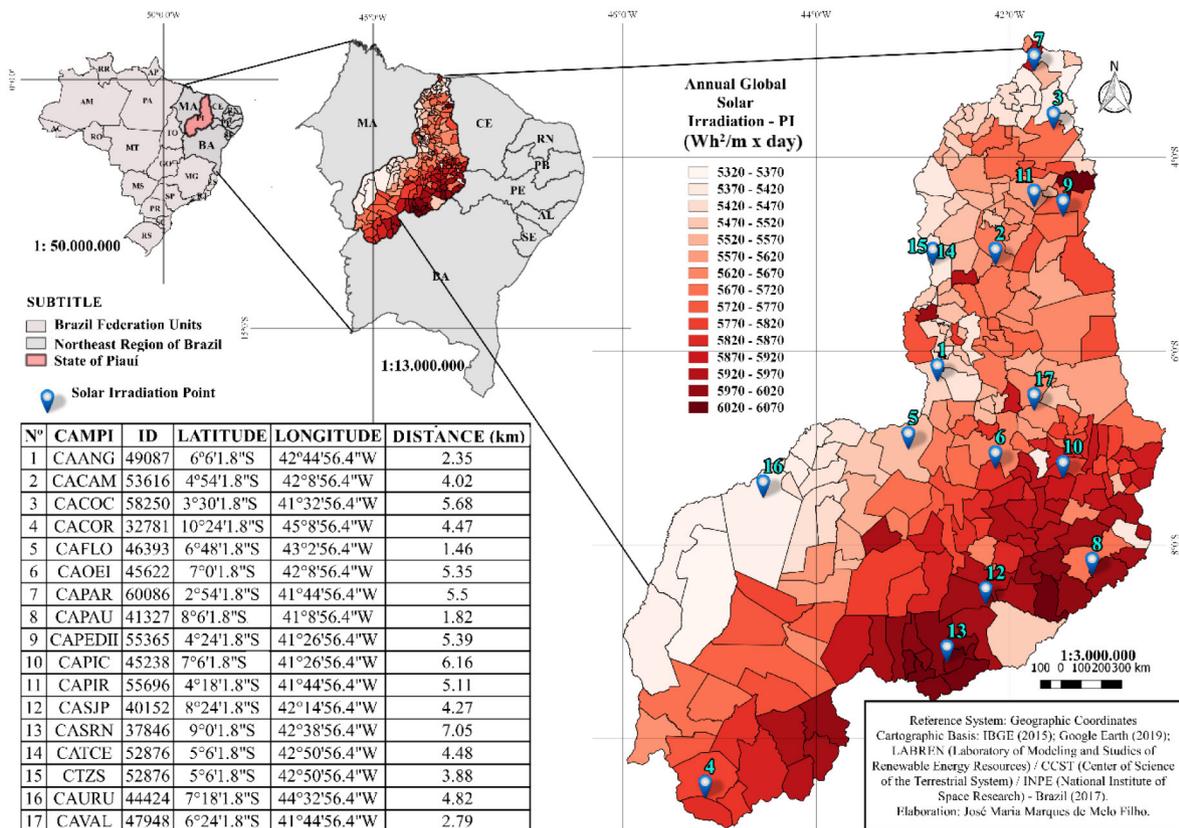


Figure 4 – Space distribution of the reference irradiation sites closest to the IFPI's campuses. Source: Prepared by the authors based on IBGE (2015), Pereira et al. (2017), and Google Earth (2018).

The energy supply contract of the campuses corresponds to the green tariff, which charges a single value for the contracted demand and distinct values for the consumed energy depending on the period of day. For the estimation of economic benefits, the GCPVSs are supposed to generate energy from the dawn until late afternoon. Therefore, the average cost of electricity during off-peak hours (from 9:30 p.m. to 5:29 p.m. of the next day) in the year 2019 was considered, resulting in an average of R\$ 0.495571/kWh, that is, 49.59% higher than the cost initially considered for the existing system. In addition, a discount rate of 0.91 was adopted for the new systems (52.35% lower), resulting in a difference between the average of the past 10 years associated with annual adjustments in the electricity tariffs and the average of the latest annual projections of the Selic rate (Figure 2). A service life of 25 years, system degradation rate of 0.8% per year, and operation and maintenance costs of 1% of the initial investment every 10 years were considered in the analysis. Thus, the return on investments is likely to occur in a maximum of 4 years, with an average BCR of 0.16, corresponding to a reduction of 78.95 and 96.34% when compared with the existing system, respectively. The IRR in this case is 34.41%, i.e., 17.01 times greater.

It is reasonable to state that the contracted expansion is viable and should be actually installed. The project presents technical-economic

conditions superior to those initially found in the year of installation of the first system in terms of higher productivity, lower BUC, more expensive energy tariffs, and lower interest rate. However, even with a difference of 2 years between the installation of the former GCPVS at the Floriano Campus and the contracting of new systems, it is noteworthy the high initial investment required for the installation of the first system, with a BUC 160% higher, that is, more than twice that of the new contracted units. It also leads to a difference of 34% involving the BUCs, which is not in compliance with the efficiency requirements established by the Sustainable Public Procurement regulated by the Brazilian government (Brasil, 2010).

Thus, to guide the expansion process of PV systems in multicampi HEIs and eliminate the temporal aspect of the analysis, also considering the identification of the closest reference point of each campus and the solar resource available in each site (Pereira et al., 2017), an expansion of the GCPVS was projected resulting from the existing systems in Table 3. The average values of the parameters associated with the systems recently contracted by the HEI were taken into account for the estimates (Table 2), as well as the minimum allowable efficiency (IFPI, 2018). This expansion is technically and economically feasible, with an estimated profit of R\$ 19,025,567.73 after an expected service life of

Table 3 – Available solar resource and estimated energy generation, reduction of carbon dioxide emissions, and electricity costs after the installation of GCPVSs.

Campus	Global solar irradiation (Wh/m ² ×day)	Annual energy generation (kWh)	Reduction of CO ₂ emissions (kg)	Energy generation ranking	Energy cost reduction (R\$)	Benefit-cost Ranking
CASRN*	5,894	136,947.63	12,051.39	1	68,127.98	1
CAPAU*	5,856	136,064.70	11,973.69	2	67,688.74	2
CASJP	5,850	135,925.28	11,961.43	3	67,616.74	3
CAPIC	5,804	134,856.47	11,867.37	4	67,110.88	4
CAOEI	5,777	134,229.12	11,812.16	5	66,770.29	5
CACOR*	5,768	134,020.01	11,793.76	6	66,668.94	6
CACAM*	5,702	132,486.49	11,658.81	7	65,903.44	7
CAPEDEII*	5,686	132,114.73	11,626.10	8	65,723.73	8
CAVAL*	5,683	132,045.02	11,619.96	9	65,683.84	9
CAPIR*	5,666	131,650.03	11,585.20	10	65,492.55	10
CAFLO**	5,641	131,069.15	11,534.09	11	65,226.14	11
CAANG	5,607	130,279.16	11,464.57	12	62,743.93	16
CAPAR	5,577	129,582.10	11,403.23	13	64,486.11	12
CATCE*	5,572	129,465.93	11,393.00	14	64,428.30	13
CTZS*	5,572	129,465.93	11,393.00	15	64,428.30	14
CACOC	5,570	129,419.46	11,388.91	16	64,382.90	15
CAURU*	5,467	127,026.24	11,178.31	17	68,127.98	17

*Contracted system; **existing system. Source: Prepared by the authors using data from Pereira et al. (2017) and Brasil (2019a).

25 years and an initial investment of R\$ 3,229,332.35, corresponding to a BCR and an IRR of 0.17 and 32.13%, respectively. It is also verified that the payback occurs 4 years after the installation.

The proposed expansion allows obtaining an average generation of 132,155.73 kWh. This amount is higher than all the energy consumed individually by any of the 17 campuses and represents 32.49% of the overall consumption. In addition, one can avoid the emission of an average of 11.63 tons of CO₂, bringing environmental benefits and enabling the creation of a ranking of technical and environmental benefits. From the energy costs for the year 2019, an average annual benefit of R\$65,483.88 could be estimated. However, since there is no uniform distribution of the solar resource in the state (Figure 4) and also that the cost of electricity may not be the same in every campus, these aspects also impact the performance of the systems in absolute terms, generating a new ranking of economic benefits.

The São Raimundo Nonato and Uruçuí Campuses presented the best and worst results, respectively. The Floriano Campus, which has a GCPVS already installed, is only in 11th position in the rankings for technical, economic, and environmental benefits. Regarding the contracted systems, it is observed that the campus with the best technical, economic, and environmental benefits (São Raimundo Nonato Campus) would be the on the top list of priorities, whereas the one with the worst indices (Uruçuí Campus) would be the last option. The Teresina Zona Sul Campus, which has the largest contracted system (120 kWp), would be only in the 14th place in terms of the economic benefits and in the 15th place with respect to technical and environmental benefits. Therefore, it is clear that the choice for the installation of systems was not based on a priority order.

The percent energy generation estimated for each campus in relation to the total consumption, as well as the percent economic benefits of the proposed systems with respect to the total energy tariff, were determined and ordered according to the first indicator in Figure 5. The average values of benefits related to consumption and electricity costs are 42.55 and 23.60%, respectively, thus creating two rankings of benefits. It is possible to observe a different ranking from the one found previously when considering only the solar resource. Even when considering the energy cost, the benefit can be seen differently in absolute or relative terms.

Finally, it is possible to obtain the metrics for the economic analysis of six scenarios provided in Table 1. The highest and lowest economic benefits were estimated for the São Raimundo Nonato and Uruçuí Campuses (R\$ 68,127.98 and R\$ 60,743.11 per year, respectively). To determine the BUC, 32 proposals from different companies that were presented to two groups of cities in the state were analyzed: four cities in the north region (Teresina, Campo Maior, Pedro II, and Piri-piri) and six cities in the south region (Uruçuí, Corrente, Paulistana, São Raimundo Nonato, and Valença do Piauí), totaling 58 proposals after the exclusion of six outliers. The highest, lowest, and average BUCs are R\$ 5.32, R\$3.48, and R\$ 4.35 per watt-peak, respectively.

From the relationship between the NPVs of capital inflows and outflows in all analyzed scenarios, one can state that the expansion is economically viable. This is due to the fact that all scenarios are located above the line that represents the financial balance, where the NPV is the same for the capital inflows and outflows (Figure 6). However, the initial investment required for the installation of the system and the return on investment varied by 52.87 and 23.05% between the best and worst cases of the analyzed scenarios (scenarios 1 and 6 in Table 4, re-

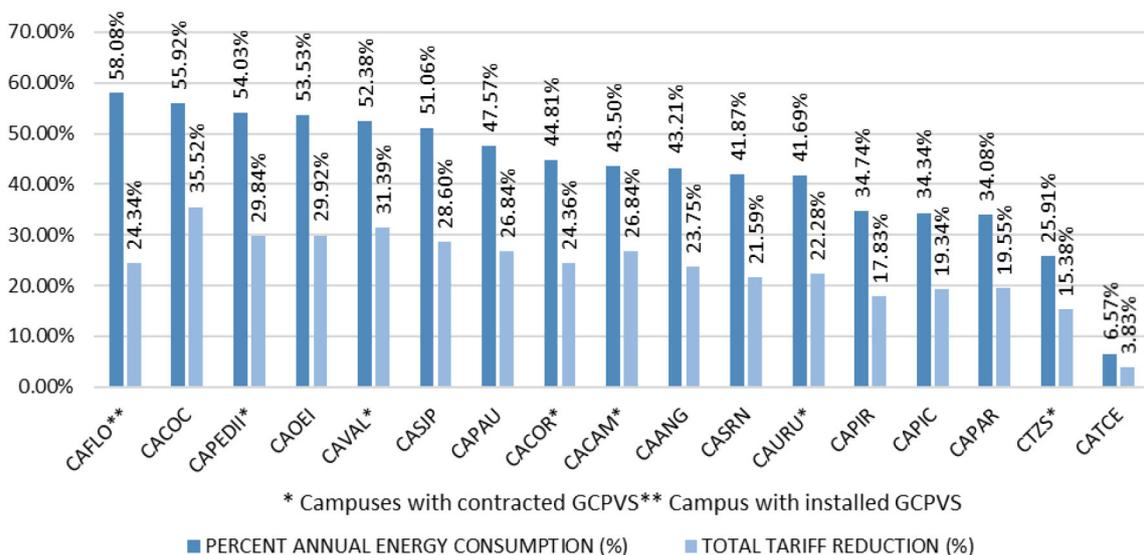


Figure 5 – Benefits related to electricity consumption and cost.

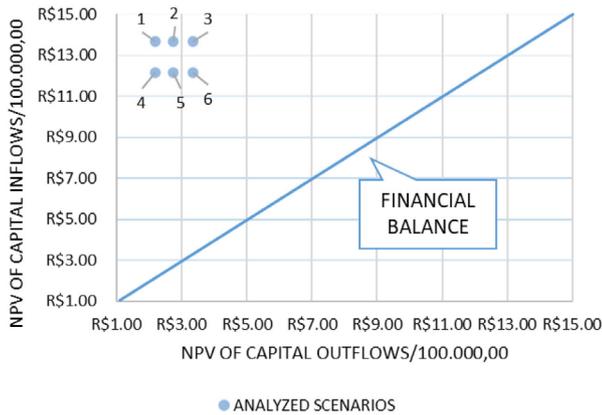


Figure 6 – Relationship between the NPVs associated with the capital inflows and outflows in the analyzed scenarios.

Table 4 – Best- and worst-case scenarios for the economic analysis of the proposed expansion.

	Scenario #1	Scenario #6
Power (kWp)	73.33	73.33
Initial investment (R\$)	216,333.33	390,133.33
Annual energy savings (R\$)	62,256.44	55,508.04
Discount rate (%)	0.91	0.91
Service life	25	25
NPV (R\$)	1,027,632.87	715,542.70
BCR	0.21	0.55
Payback (years)	4	8
IRR (%)	26.49	11.62

spectively), causing a negative impact on the economic efficiency of the projects.

From one scenario to the other, the payback time increased by 50% and the BCR increased by 98.66%, decreasing the IRR by 45.17%. Thus, considering the economy of scale when contracting new systems, the lowest BUC should be chosen so as to achieve metrics similar to those found in scenario 1 (Table 1), since the natural tendency is that the higher the system power, the lower the BUC (Brito and Melo, 2018).

Conclusion

This work has presented a thorough analysis of a GCPVS installed at the Floriano Campus of the IFPI, as well as the expansion contracted by the institution in 2020. The first system was found to be the first mini-generation system installed in the state of Piauí, while presenting technical feasibility, good merit indices, and solid strategic adherence.

It also represents a significant project that meets the expectations of the institution associated with education, research, and extension activities.

However, the economic feasibility of the system must be carefully analyzed. Even with a positive NPV, the project has a high payback time and a high BCR due to the high initial investment. The study demonstrated that contracted expansion is feasible and should be encouraged, with technical-economic conditions superior to those initially found in the year of installation of the first PV system. In other words, the new systems present prominent characteristics in terms of higher productivity, lower BUC, a more expensive energy tariff, and lower interest rate.

It was possible to use a solar atlas to verify the feasibility of expanding the PV systems in a multicampi HEI. Thus, one could identify the cities in the state of Piauí with the highest generation potential, which are located in the southeast region. The study has also confirmed the technical-economic feasibility and the great strategic adherence, in addition to the possible benefits associated with the reduction of energy costs, implementation of sustainable environmental practices, and support to the core activity of the institution, especially in the aforementioned region.

The methodology is quite effective in identifying investment priorities in PV solar energy, also enabling the creation of rankings of benefits that consider the energy generation and cost reduction in absolute and relative values, reduction in CO₂ emissions, as well as economic metrics. However, even with the possibility of creating rankings, such technical criteria may not be sufficient, since they are not decisive in defining a solid criterion for the HEI under study. Thus, it was not possible to choose exactly in which campus the GCPVS should be installed first, this being the scope of future work.

From the perspective of sustainable public procurement, one should also ensure equality, efficiency in public spending, and the promotion of sustainable development to analyze the bidding processes associated with the PV systems. The reasons for the differences in implementation costs and the choice of installation sites with lower technical, economic, and environmental returns should be understood in order to determine alternatives aiming at the better cost-effectiveness of future systems. This is especially important considering the economy of scale, since the larger the system, the lower the BUC. No ranking is definitive and there is no default size for the GCPVS to be installed. The best option for the manager is to analyze all scenarios and determine the best option.

Based on the present study, it is possible to recommend the installation of small systems (microgeneration) in the campuses that provide less technical and economic benefits for promoting the environmental education. Such actions should encourage the creation of a sustainable educational space and bring benefits to teaching, research, and extension activities. The largest investments should primarily focus on campuses where the greatest technical, economic, and environmental benefits exist. Finally, it is expected that this methodology can be applied in other multicampi HEIs and guide the implementation and expansion of PV systems, bringing environmental benefits and contributing to the achievement of SDGs.

Contribution of authors:

Silva, O. A. V. O. L.: Formal analysis, Methodology, Resources, Software, Writing – original draft, Writing – review & editing. Moita Neto, J. M.: Funding acquisition, Project administration. Lira, M. A. T.: Supervision, Validation, Visualization, Writing – review & editing. Morais, F. H. M.: Conceptualization, Data curation, Investigation.

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