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ANÁLISE DE DESEMPENHO E VIABILIDADE TÉCNICO-FINANCEIRA DE UMA MICROGERAÇÃO DISTRIBUÍDA DE 75 KW INSTALADA NO CAMPUS CEDRO DO INSTITUTO FEDERAL DE EDUCAÇÃO, CIÊNCIA E TECNOLOGIA DO CEARÁ

PERFORMANCE ANALYSIS AND TECHNICAL-FINANCIAL FEASIBILITY OF A 75 KW DISTRIBUTED MICROGERATION INSTALLED AT IFCE-CEDRO CAMPUS

ANÁLISIS DE DESEMPEÑO Y VIABILIDAD TÉCNICO-FINANCIERA DE UNA MICROGENERACIÓN DISTRIBUIDA DE 75 KW INSTALADA EN EL CAMPUS CEDRO DEL INSTITUTO FEDERAL DE EDUCAÇÃO, CIÊNCIA E TECNOLOGIA DO CEARÁ

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Resumo

Este estudo apresenta uma análise de desempenho e da viabilidade técnico-financeira de um sistema fotovoltaico conectado à rede instalado no Campus Cedro do Instituto Federal de Educação, Ciência e Tecnologia do Ceará (IFCE). O sistema possui potência nominal de 75 kW e potência instalada de 92,43 kWp, sendo classificado como uma unidade de microgeração distribuída. A pesquisa avaliou parâmetros técnicos como geração média diária mensal, irradiação solar média, Yield, Performance Ratio (PR) e Capacity Factor (CF), utilizando dados operacionais do ano de 2021. Os resultados mostraram geração anual de 149.059,4 kWh, com média mensal de 12.421,6 kWh e Yield médio de 137,77 kWh/kWp. O PR médio anual foi de 74,80% e o CF médio, calculado sobre a potência CC instalada, foi de 18,60%, indicando desempenho satisfatório do sistema fotovoltaico. A análise financeira, baseada em um cenário de referência (consumo de 2019 valorado com a geração

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observada em 2021), estimou uma economia média mensal de R$ 5.157,08 e uma economia anual de R$ 61.885,07 na fatura de energia elétrica da instituição. Com as premissas adotadas (investimento inicial de R$ 380.659,66, horizonte de 25 anos, taxa de desconto de 11,45% a.a., reajuste tarifário médio de 10,19% a.a. e degradação de 0,8% a.a.), o investimento apresentou Valor Presente Líquido (VPL) de R$ 844.287,15, Taxa Interna de Retorno (TIR) de 26,72% e payback descontado de aproximadamente 6,6 anos. A análise de sensibilidade indicou VPL positivo em todos os cenários individuais avaliados, sendo o reajuste tarifário a variável de maior influência: sem reajuste, o VPL cai para cerca de R$ 93 mil e o payback descontado sobe para 12,3 anos. Possíveis perdas por limitação de potência do inversor (clipping) e por sujidade dos módulos não foram medidas nem quantificadas neste estudo e permanecem como hipóteses. Recomenda-se a limpeza periódica dos módulos como boa prática de manutenção e a avaliação da ampliação do sistema para reduzir os custos com eletricidade.
Palavras-chave: energia solar fotovoltaica; microgeração distribuída; viabilidade financeira;

Abstract

This study presents a performance analysis and the technical-financial feasibility of a grid-connected photovoltaic (GCPV) system installed at the Cedro Campus of the Federal Institute of Education, Science and Technology of Ceará (IFCE). The system has a nominal power of 75 kW and an installed capacity of 92.43 kWp, being classified as a distributed microgeneration unit. The research evaluated technical parameters such as average daily monthly generation, average solar irradiation, Yield, Performance Ratio (PR), and Capacity Factor (CF), using operational data from the year 2021. The results showed an annual generation of 149,059.4 kWh, with a monthly average of 12,421.6 kWh and an average Yield of 137.77 kWh/kWp. The annual average PR was 74.80%, and the average CF, calculated on the installed DC power, was 18.60%, indicating satisfactory performance of the photovoltaic system. The financial analysis, based on a reference scenario (2019 consumption valued with the generation observed in 2021), estimated average monthly savings of R$ 5,157.08 and annual savings of R$ 61,885.07 on the institution's electricity bill. Under the adopted premises (initial investment of R$ 380,659.66, 25-year horizon, discount rate of 11.45% per year, average tariff adjustment of 10.19% per year and degradation of 0.8% per year), the investment presented a Net Present Value (NPV) of R$ 844,287.15, an Internal Rate of Return (IRR) of 26.72%, and a discounted payback period of approximately 6.6 years. The sensitivity analysis indicated a positive NPV in all individual scenarios evaluated, the tariff adjustment being the most influential variable: without any adjustment, the NPV falls to approximately R$ 93 thousand and the discounted payback increases to 12.3 years. Possible losses due to inverter power limitation (clipping) and module soiling were neither measured nor quantified in this study and remain hypotheses. Periodic module cleaning is recommended as a good maintenance practice, as well as evaluating the expansion of the system to reduce electricity costs.
Keywords: photovoltaic solar energy; distributed microgeneration; financial feasibility.

Resumen

Este estudio presenta un análisis de desempeño y de la viabilidad técnico-financiera de un sistema fotovoltaico conectado a la red instalado en el Campus Cedro del Instituto Federal de Educación, Ciencia y Tecnología de Ceará (IFCE). El sistema posee una potencia nominal de 75 kW y una capacidad instalada de 92,43 kWp, siendo clasificado como una unidad de microgeneración distribuida. La investigación evaluó parámetros técnicos como generación media diaria mensual, irradiación solar media, Yield, Performance Ratio (PR) y Capacity Factor (CF), utilizando datos operativos del año 2021. Los resultados mostraron una generación anual de 149.059,4 kWh, con un promedio mensual de 12.421,6 kWh y un Yield promedio de 137,77 kWh/kWp. El PR promedio anual fue de 74,80% y el CF promedio, calculado sobre la potencia CC instalada, fue de 18,60%, indicando un desempeño satisfactorio del sistema fotovoltaico. El análisis financiero, basado en un escenario

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de referencia (consumo de 2019 valorado con la generación observada en 2021), estimó un ahorro promedio mensual de R$ 5.157,08 y un ahorro anual de R$ 61.885,07 en la factura de energía eléctrica de la institución. Con los supuestos adoptados (inversión inicial de R$ 380.659,66, horizonte de 25 años, tasa de descuento de 11,45% al año, ajuste tarifario promedio de 10,19% al año y degradación de 0,8% al año), la inversión presentó un Valor Presente Neto (VPN) de R$ 844.287,15, una Tasa Interna de Retorno (TIR) de 26,72% y un período de recuperación descontado de aproximadamente 6,6 años. El análisis de sensibilidad indicó un VPN positivo en todos los escenarios individuales evaluados, siendo el ajuste tarifario la variable de mayor influencia: sin ajuste, el VPN cae a cerca de R$ 93 mil y el período de recuperación descontado sube a 12,3 años. Las posibles pérdidas por limitación de potencia del inversor (clipping) y por suciedad de los módulos no fueron medidas ni cuantificadas en este estudio y permanecen como hipótesis. Se recomienda la limpieza periódica de los módulos como buena práctica de mantenimiento y la evaluación de la ampliación del sistema para reducir los costos de electricidad.
Palabras clave: energía solar fotovoltaica; microgeneración distribuida; viabilidad financiera.

1. Introduction

Brazil has one of the cleanest electricity generation mixes, according to [4]. The 2022 National Energy Balance (BEN) shows that about 88% of the country's domestic electricity supply is renewable. Hydroelectric power accounts for 61.9%, followed by wind (11.8%) and solar (4.4%). Among the non-renewable sources are natural gas (6.1%), coal (1.2%), nuclear (2.1%), and oil derivatives (0.9%). Solar energy's share, although still small, grew from 0.13% in 2017 to 4.4% in 2022 (EPE,2017), (EPE, 2020) e (EPE, 2021).

Brazil's electricity grid is characterized by centralized generation in large hydroelectric plants and a lack of diversification, with a high dependence on hydropower. Most of these plants are connected to consumption centers via the transmission system (Aneel, 2015). Grid-connected photovoltaic systems (PV systems, also referred to as distributed generation) offer an alternative to decentralize and diversify electricity supply, in addition to helping to reduce energy losses in the National Interconnected System (SIN), which are caused by the long distance between power plants and consumption centers (Absolar, 2020).

In this context, alternatives are being evaluated to diversify the electricity matrix, focusing on distributed generation from renewable energy sources (RES) to find solutions for potential future energy supply problems and to ensure energy security in the sector. Environmental concerns and energy efficiency have driven the rapid growth of RES, both in Brazil and worldwide. Another relevant factor is the

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increase in electricity demand, as well as the future prospect of RES for applications such as green hydrogen (H2V) production, along with rising price of kWh above inflation. It is expected that RES can help reduce the cost of electricity (Montenegro, 2013).

Thus, based on the advantages offered by Normative Resolution No. 1059 of February 7, 2023 (REN 1.059/2023) and Law 14.300/2022, which improve the conditions for people to generate their own energy, it is possible to connect PV systems to the utility's grid. This connection occurs through the energy compensation system, where electricity generated by a consumer unit (CU) is injected into the local utility's grid via microgeneration or mini-distributed generation. The energy provided as a free loan can be used later to offset consumption or counted as energy credits for CU's in the system (Aneel, 2023) e (Brazil, 2022).

Micro and mini-distributed generation (MMGD) is no longer considered a small sector in the country, as investments exceeded R$ 2 billion in 2018 alone. In 2019, this sector had an installed capacity of 2.12 GW, in 2020 an installed capacity of 4.38 GW, in 2023 the country reached the 22.4 GW of installed solar capacity, and in September 2024 it surpassed 31.9 GW of installed power (Absolar, 2021), (Absolar, 2022) e (Absolar, 2024).

Distributed microgeneration is defined as an alternating current generating plant with an installed capacity of less than or equal to 75 kW that uses renewable energy sources or qualified cogeneration, connected to the electricity distribution grid through CU installations (Aneel, 2012). Distributed minigeneration, on the other hand, is defined as an alternating current generating plant with an installed capacity greater than 75 kW, up to 5 MW for dispatchable sources and up to 3 MW for non-dispatchable sources, that uses renewable energy sources or qualified cogeneration, connected to the electricity distribution grid through CU installations (Brazil, 2022).

The performance analysis of a PV systems, which is often totally or partially neglected, is essential to obtain parameters such as: average monthly energy generated, productivity, performance ratio, and capacity factor, making it possible to compare the performance of PV systems across different regions, equipment, and capacities (Vasiliev e Nur-e-alam, 2019).

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This study aims to conduct a comprehensive analysis of the performance and technical and financial feasibility of implementing a distributed solar photovoltaic microgeneration system (grid-connected PV system) at the Federal Institute of Education, Science and Technology of Ceara (IFCE) - Cedro Campus.

2. Methodology

2.1 Study location

The location chosen for the study was the Federal Institute of Education, Science and Technology of Ceara (IFCE), Cedro Campus, located in the south-central region of Ceara. The latitude and longitude of the chosen site are 6°36'03.2"S and 39°03'17.8"W, respectively (Google maps, 2023). See Figure 1.

Figure 1 - Photograph of IFCE-Cedro Campus.



Source: IFCE (2023).

2.2 Mathematical Formulation

2.2.1 Net Present Value

The net present value (NPV) represents the sum of the project's cash flows discounted to the present value. In this formula, I_0 is the initial investment of the project (R$), i is the discount rate (decimal, per year), n is the time period (year), N is the analysis horizon (years), and FC_n is the cash flow in period n (R$). It can be

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calculated according to Eq. (1).

$$NPV = \sum_{n=1}^{N} \frac{FC_n}{(1+i)^n} - I_0 \quad (1)$$

2.2.2 Internal Rate of Return

The internal rate of return (IRR) is the discount rate that makes the NPV equal to zero. At this point, the value of I_0 is equal to the sum of the present values of the cash flows. In this formula, I_0 is the initial investment (R$), n is the time period (year), N is the analysis horizon (years), and FC_n is the cash flow in period n (R$). It is calculated according to Eq. (2).

$$I_0 = \sum_{n=1}^{N} \frac{FC_n}{(1+IRR)^n} \quad (2)$$

2.2.3 Payback

Payback is the period required to recover the initial investment. In this study, the discounted payback (PB_d, in years) is used, that is, the cash flows are discounted at the rate i before being accumulated. In Eq. (3), t is the first year in which the cumulative present value of the cash flows becomes greater than or equal to I_0, I_0 is the initial investment (R$) and FC_n is the cash flow in year n (R$). The term $(t-1)$ accounts for the full years before the recovery, and the fraction corresponds to the part of year t needed to recover the remaining balance (linear interpolation within the year).

$$PB_d = (t-1) + \frac{I_0 - \sum_{n=1}^{t-1} \frac{FC_n}{(1+i)^n}}{\frac{FC_t}{(1+i)^t}} \quad (3)$$

2.2.4 Monthly average daily generation

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To size the grid-connected PV system, it is necessary to calculate the monthly average daily generation, G_m, where G_m (kWh/day) is the average of the daily generations over all measured days. G_{day} is the total generation of the day, and n is the number of days in the month with measurements. In this case, m equals n, as seen in Eq. (4). By obtaining the G_m, you can determine the average amount of energy generated per day by the PV plant. See Eq. (4) (Costa et al, 2019). Here, G_day is expressed in kWh, and n and m are numbers of days.

$$G_m = \frac{\sum_{k=1}^{m} G_{day}}{n} \quad (4)$$

2.2.5 Monthly average solar irradiation of the location

According to Eq. (5), the average monthly irradiation $\mathrm{I_m}$ (kWh/m²·day) represents the mean solar irradiation at the study site. Here, $\mathrm{I_{day}}$ is the total daily irradiation (kWh/m²), and n is the number of days in the month with measurements (EPE, 2017).

$$I_m = \frac{\sum_{k=1}^{n} I_{day}}{n} \quad (5)$$

2.2.6 STC Irradiance

Most studies on estimating the generation parameters of photovoltaic modules are conducted under Standard Test Conditions (STC). STC is standardized for testing PV modules with an irradiance (I_{STC}) of 1,000 W/m², a temperature of 298 K, a wind speed of 1.5 m/s, and a standard spectral distribution for an air mass of 1.5. It is well known that PV modules do not operate under these conditions, which are considered ideal. However, to obtain parameters that ensure better accuracy in controlling the actual power generated by the PV module, it is necessary to develop methods that update based on climate variations (Lopes Filho et al, 2018).

2.2.7 Peak Sun Hours (PSH)

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Eq. (6) shows the time interval in hours during which solar irradiation is concentrated throughout the day, known as Peak Sun Hours (PSH). It uses a constant solar irradiance parameter of 1000 W/m² (Siqueira, 2015). To get the Peak Sun Hours (PSH), the ratio of the monthly irradiance (I_m) to the STC irradiance (I_{STC}) is taken based on the STC parameters. PSH is considered a reference for productivity. Since I_m is expressed in kWh/m²·day and I_STC is equal to 1 kW/m², PSH is expressed in hours per day (h/day).

$$PSH = \frac{I_m}{I_{STC}} \tag{6}$$

2.2.8 Yield

Eq. (7) shows the relationship between the total energy generated in the period (E_G), in kWh, and the installed PV power of the modules (P_dc), in kWp. For the monthly yield, E_G is the total energy generated in the month, which is different from the monthly average daily generation G_m (kWh/day) defined in Eq. (4). When compared over a one-year operation, it is more commonly known as the annual yield. In this study, the yield was calculated for each of the twelve months, and the annual average is the arithmetic mean of the twelve monthly values (Urbanetz e Casagrande, 2014).

$$Y = \frac{E_G}{P_{dc}} \left(\frac{kWh}{kWp}\right) \tag{7}$$

2.2.9 Performance Ratio

Eq. (8), expressed as a percentage, shows the relationship between yield (kWh/kWp) and the monthly average PSH at 1,000 W/m² incident on the PV modules. Δt represents the number of days in the month. The performance ratio (PR) is usually calculated on an annual basis, called the annual performance ratio, but it can also be considered the monthly performance ratio (Urbanetz e Casagrande, 2014). Since Y is expressed in kWh/kWp, PSH in h/day and Δt in days, PR is dimensionless and is expressed as a percentage.

$$PR = \frac{Y}{PSH \cdot \Delta t} \ (\%) \tag{8}$$

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The performance ratio is a dimensionless index that shows the total losses, failures, and variations that are intrinsic to PV systems. For example, the decrease in efficiency due to the increased operating temperature of solar cells cannot be considered a failure; it is a consequence of the variation of the semiconductor's electronic properties with temperature. This factor indicates how closely the system operates compared to an ideal reference system ($PR = 1$). With this method, it is possible to compare system indices without interference from geographical location, generator positioning, or nominal capacity, because productivity is normalized in relation to solar irradiation (Nóbrega et all, 2019).

2.2.10 Capacity Factor

The capacity factor (CF), shown in Eq. (9), is the ratio between a given plant's effective generation (E_G) over a specific period and its maximum total capacity during that same period, assuming the system could operate at its P_{dc} continuously, 24 hours a day throughout the period Δt (Urbanetz e Casagrande, 2014). This indicator allows the comparison of generation efficiency among different energy sources (Montenegro, 2013). In this study, P_dc = 92.43 kWp is the installed DC power of the PV modules (and not the 75 kW AC nominal power of the inverters), the same reference adopted for the Yield (Eq. 7) and the PR (Eq. 8). E_G is expressed in kWh, P_dc in kW and Δt in days, so that CF is dimensionless and expressed as a percentage. The annual CF is the arithmetic mean of the twelve monthly CF values.

$$CF = \frac{E_G}{P_{dc} * 24 * \Delta t} \ (\%) \tag{9}$$

2.2.11 Levelized Cost of Energy (LCOE)

The LCOE (Levelized Cost of Energy) is a widely used indicator for evaluating the economic feasibility of electric power generation systems. This parameter represents the average cost of energy production over the entire lifetime of the project, considering the initial investments, operation and maintenance costs,

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discount rate, and the total energy generated by the system.

In Eq. (10), the formula for calculating the $LCOE$ can be observed, where C_t represents the costs in year t, including investments, operation, and maintenance of the system, while $E_t$corresponds to the energy generated during the same period. Furthermore, the variable $i$represents the discount rate used in the economic analysis, and n corresponds to the lifetime of the project. Therefore, the $LCOE$ expresses the average cost of energy generation throughout the entire life cycle of the system. C_t is expressed in R$, E_t in kWh, i in decimal form per year, and t and n in years, so that the LCOE is given in R$/kWh. In this study, the numerator contains only the initial investment (C_0 = I_0, with C_t = 0 for t ≥ 1), that is, operation and maintenance costs and equipment replacement were not included in the base case. The denominator considers the energy generated in the first year (149,059.4 kWh, measured in 2021), reduced by the annual degradation rate of 0.8% in the following years, with E_0 = 0 and no change in the solar resource over the project lifetime.

$$LCOE = \frac{\sum_{t=0}^{n} \frac{C_t}{(1+i)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+i)^t}} \quad (10)$$

2.2.12 Cash flow premises and sensitivity analysis

The cash flow of the base case is built from the savings estimated for the base year, FC_0 = R$ 61,885.07 (Section 4.6), which grows at a constant annual rate, as shown in Eq. (11). In this equation, r_t is the average annual tariff adjustment (10.19% per year, equal to the cumulative increase of 50.99% over five years divided by five) and δ is the annual degradation of the modules (0.8% per year; Souza e Penha, 2020), so that the cash flow grows 9.39% per year. The initial investment is I_0 = R$ 380,659.66, the analysis horizon is N = 25 years and the discount rate is i = 11.45% per year, based on the historical average of the Selic rate. The base case does not include operation and maintenance costs or equipment replacement costs.

$$FC_n = FC_0(1 + r_t - \delta)^n \quad (11)$$

The sensitivity analysis varies one premise at a time, keeping the others at the

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base-case values: (i) the discount rate, from 8% to 15% per year; (ii) the annual tariff adjustment, from 0% to 10.19% per year, including the compound rate of 8.59% per year equivalent to the historical cumulative increase of 50.99% over five years; (iii) the annual generation, from −20% to +5% in relation to the 149,059.4 kWh of the base case, with the savings varying proportionally; and (iv) the annual operation and maintenance cost, from 0.5% to 1.5% of the initial investment per year, assumed constant in nominal terms and subtracted from the annual cash flow. For each case, the NPV (Eq. 1), the IRR (Eq. 2) and the discounted payback (Eq. 3) are recalculated. In addition, a conservative, a central (base case) and an optimistic scenario combine unfavorable or favorable values of these variables simultaneously.

3. Characterization Of The Analyzed Grid-Connected Pv System

3.1 Standard Input

The CU is connected to a medium-voltage distribution line operated by ENEL Ceara, with a connection voltage of 13.8 kV. Additionally, it has its own 450 kVA substation with two 225 kVA transformers connected in parallel, providing a secondary voltage of 380/220 V.

3.2 Classification of the grid-connected PV system

The CU belongs to Group A, as defined by the Brazilian electricity regulatory framework, which includes medium and high-voltage consumers such as industries, large companies, and shopping malls. It has a contracted demand of 216 kW and a photovoltaic generation capacity of 75 kW; therefore, the grid-connected PV system is classified as distributed microgeneration. Since the contracted demand is greater than the grid-connected PV system capacity (75 kW), there is no need to contract the Distribution System Usage Tariff for microgeneration (TUSDg), a tariff category applied in Brazil.

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3.3 Photovoltaic modules

The system uses monocrystalline photovoltaic modules, model JAM72S09-390/PR, manufactured by JA Solar. A total of 237 modules were installed. The technical specifications of these modules are: a maximum nominal power of 390 W, an open-circuit voltage of 49.35 V, a maximum power voltage of 40.21 V, a short-circuit current of 10.22 A, a maximum power current of 9.70 A, and an efficiency of 19.50%. The installed module power is 92.43 kWp. The modules arrangement is shown in Figure 2.

Figure 2. Top view of the PV module layout.



Source: Jornal A Praça (2020).

3.4 Inverters

Inverters play an important role in grid-connected PV systems, converting the energy generated by the modules from direct current (DC) to alternating current (AC). Two inverter models are used: the GW50KN-MT, referred to as Inverter 1, which has a maximum DC input power (Pmax) of 61.23 kWp and an AC output power of 50 kW. The GW25K-MT, referred to as Inverter 2, has a Pmax of 31.2 kWp and an AC output power of 25 kW. Both are from the manufacturer GoodWe. Inverter 1 has four Maximum Power Point Tracking (MPPT) inputs, and inverter 2 has three MPPT

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inputs. The distribution of modules is shown in Table 1.

TABLE 1. Distribution of modules across the MPPT inputs of the inverters.

Inverter 1				
	MPPT 1	MPPT 2	MPPT 3	MPPT 4
Modules in series	15	16	16	16
Parallel strings	3	3	2	2
Total modules	45	48	32	32
Inverter 2				
	MPPT 1	MPPT 2	MPPT 3	
Modules in series	16	16	16	
Parallel strings	2	2	1	
Total modules	32	32	16	

3.5 Scaling factor of the Grid-Connected PV System

Fig. 3 shows a simplified diagram of the structure and electrical installation of the grid-connected PV system at IFCE-Cedro Campus. It is possible to see that the grid-connected PV system generation begins with two sets of PV modules. Each set connects to a different inverter, which then delivers power to the PV system AC panel, where the AC protections are located. From there, power is directed to the General Power Panel and then to the Main Low Voltage Switchboard (QGBT). It is subsequently distributed to supply both the loads of the IFCE-Cedro Campus facilities and its own 450 kVA substation, which has two 225 kVA transformers, providing a secondary voltage of 380/220 V. Finally, the power is sent to a bidirectional meter and injected into the distribution grid operated by ENEL Ceara.

Inverter 1 has a nominal power of 50 kW, connected to 157 PV modules, forming Subsystem 1 with an installed power of 61.23 kWp. It features four MPPT inputs, each associated with different module arrangements, along with String Boxes that include DC surge protection devices, fuses, and disconnectors.

Inverter 2 has a nominal power of 25 kW, connected to 80 PV modules, with

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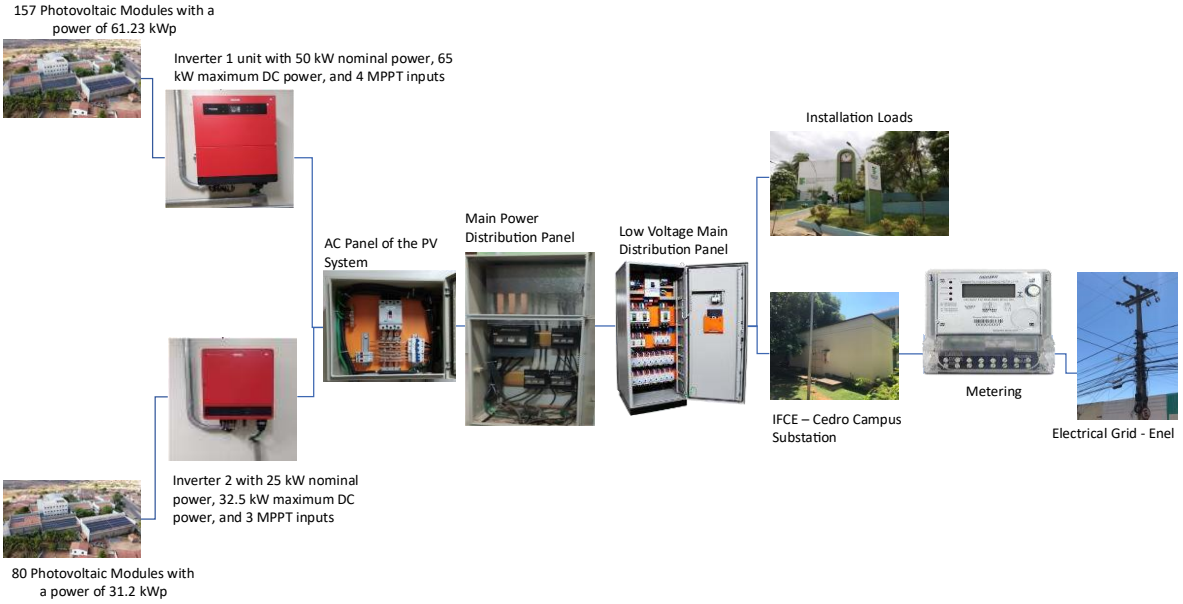
three MPPT inputs—fewer than Inverter 1—and also includes String Boxes with DC protection devices and disconnectors. The specifics arrangements of modules in strings are detailed in Table 1.

Figure 3. Representative diagram of the grid-connected PV system at IFCE-Cedro Campus.



Source: Authors.

4. Results And Discussions

4.1 Electricity Consumption Data of IFCE – Cedro Campus

The COVID-19 pandemic drastically reduced energy consumption at IFCE-Cedro Campus starting in March 2020 due to social distancing and the shift to remote learning, which lasted until early 2022. Therefore, this study uses consumption data from before this drop, covering the period from January to December 2019. We analyzed consumption during peak hours (PH), off-peak hours (OPH), and total consumption (kWh). The results are shown in Figure 4 to illustrate the 2019 annual profile.

Figure 4. Graphical representation of the total electricity consumption of IFCE-Cedro Campus.

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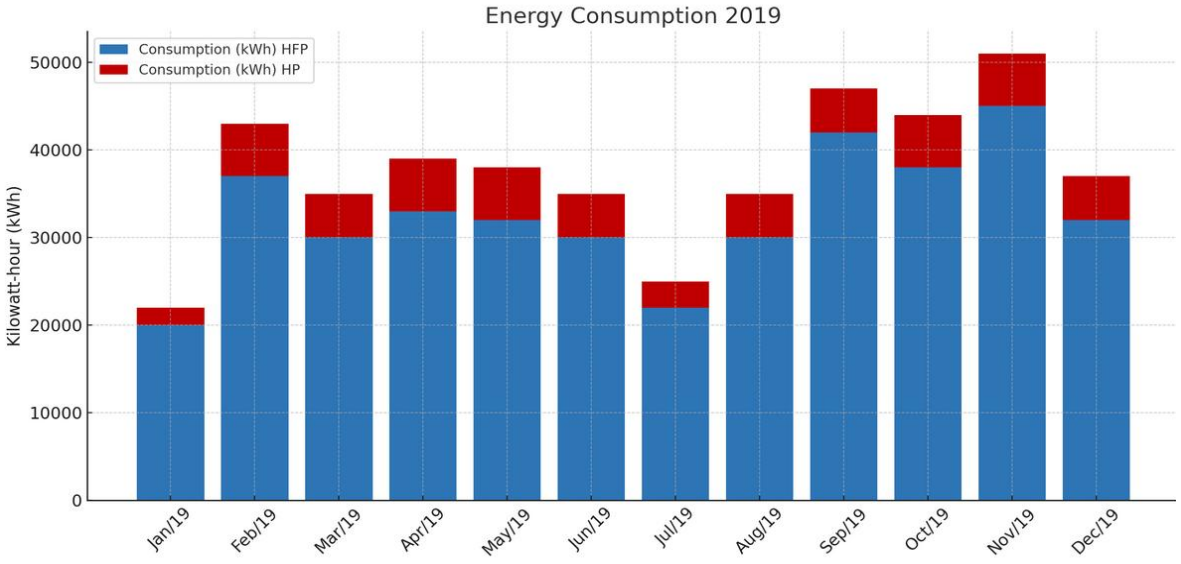

Source: Authors.

Figure 4 shows the variations in energy consumption at IFCE-Cedro Campus in 2019. November had the highest total consumption, at 52,039.0 kWh, due to increased use of air conditioning during the hotter months. In January, consumption was the lowest of the year, at 22,094.0 kWh (20,320 kWh OPH and 2,629 kWh PH), reflecting the holiday period. The total consumption for 2019 was 448,470 kWh, with a monthly average of 37,372.5 kWh.

4.2 Data Collected from the Grid-Connected PV System

The generation is linked to the solar irradiation values at the study site. Therefore, generation data were obtained through the monitoring platform of the IFCE-Cedro Campus grid-connected PV system. The monitoring platform belongs to the installed inverters, so the data correspond to the active energy in alternating current (AC) generated at the inverter output, before it is distributed between instantaneous self-consumption on Campus and injection into the grid (Figure 3). The generation data used in this study refer to the year 2021.

According to Figure 5, August and September had the highest generation, with 13,932.1 kWh and 14,050.7 kWh, respectively. The months of January and February had the lowest generation, as they coincide with the rainy season, with a generation

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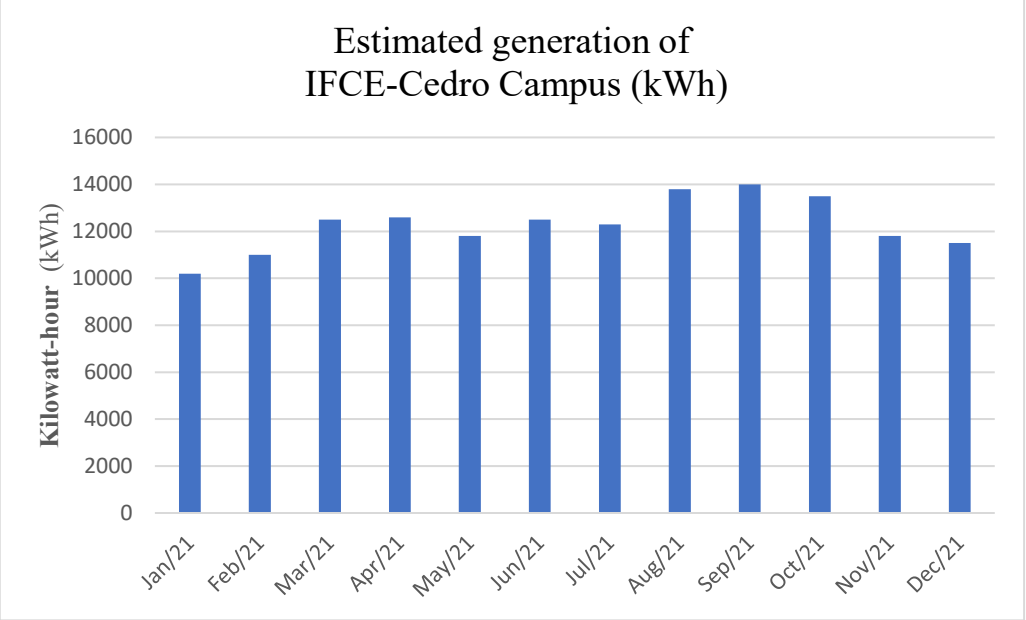
value of 10,167.2 kWh and 10,866.5 kWh, respectively. The total annual generation was 149,059.4 kWh, with a monthly average of 12,421.6 kWh.

Figure 5. Graphical representation of the estimated electricity generation of IFCE-Cedro Campus.



Source: Authors.

4.3 Generation and Irradiance Trend

Figure 6. compares the generation and solar irradiation at the IFCE-Cedro Campus grid-connected PV system. The generation follows the monthly irradiation, with lower values at the beginning of the year, increasing from August, peaking in September, and stabilizing in December. In November, generation was lower than expected, possibly due to system shutdowns or grid-related interruptions on Campus, which affected data collection.

Figure 6. Graphical representation of PV generation vs. solar irradiation.

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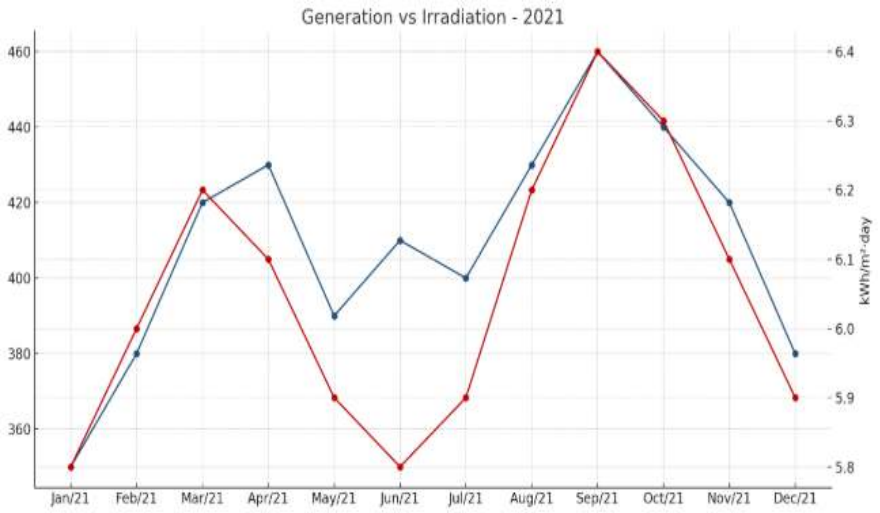
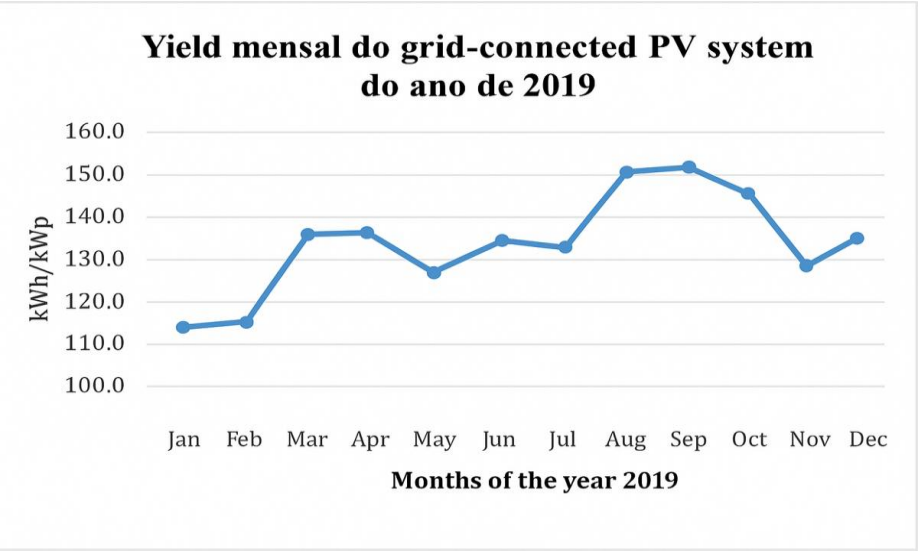


Source: Authors.

4.4 Yield and Performance Ratio of the Grid-Connected PV System

Figure 7 shows the specific yield based on the installed power of 92.43 kWp. August and September had the highest productivity, with 150.73 kWh/kWp and 152.01 kWh/kWp, respectively, while January and February recorded the lowest values, with 116.49 kWh/kWp and 117.56 kWh/kWp. The annual average was 137.77 kWh/kWp. This value is the arithmetic mean of the twelve monthly yields, each calculated as the monthly generation divided by the installed DC power (Eq. 7).

Figure 7. Graphical representation of monthly yield data for 2021.



Source: Authors.

Figure 8 shows the monthly PR of the grid-connected PV system, with a peak

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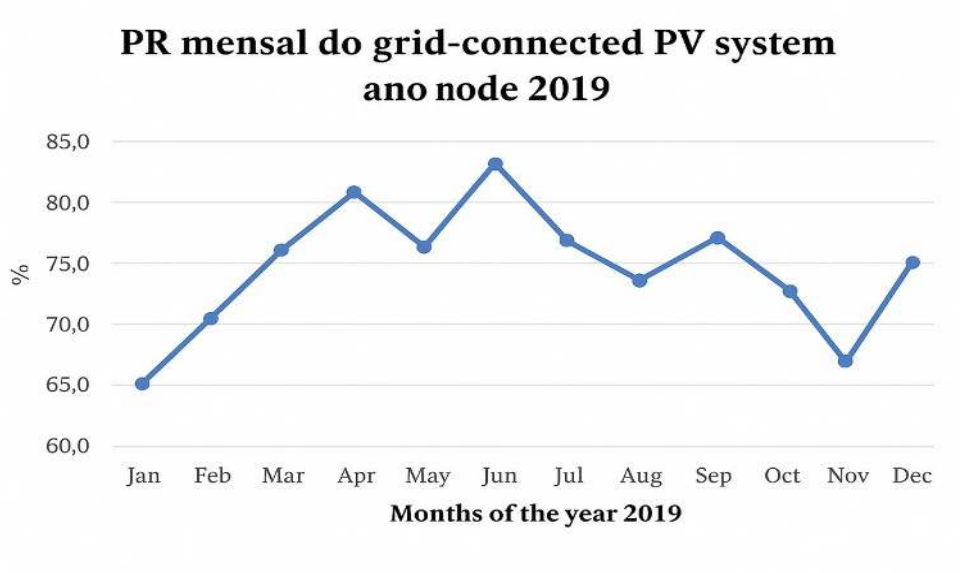
of 83.10% in June and a minimum of 66.39% in January. The annual average is 74.80%, indicating good alignment between productivity and solar resource availability. In November, there was an unexpected drop in the PR, whose cause could not be confirmed with the available data. Possible factors include higher module temperatures, interruptions in the grid or in data collection, and power limitation by the inverters (clipping). The installed DC power (92.43 kWp) is 23.24% higher than the AC nominal power of the inverters (75 kW), a DC/AC ratio of 1.23. This ratio is a design characteristic that indicates a potential for inverter saturation at times of high irradiance, but it does not by itself quantify energy losses, and no operational records of clipping events were available to confirm or measure them.

Figure 8. Graphical representation of monthly PR data.



Source: Authors.

4.5 CF Data of the Grid-Connected PV System

September had the highest average daily electricity generation, which is directly reflected in its CF, the highest of the year at 21.11%. As shown in Figure 9, the CF grows from July to September, and then declines after September, stabilizing in December. The lowest CF value was 15.66% in January, the month when the rainy season begins. The average CF for the year 2021 was 18.60%. The CF was

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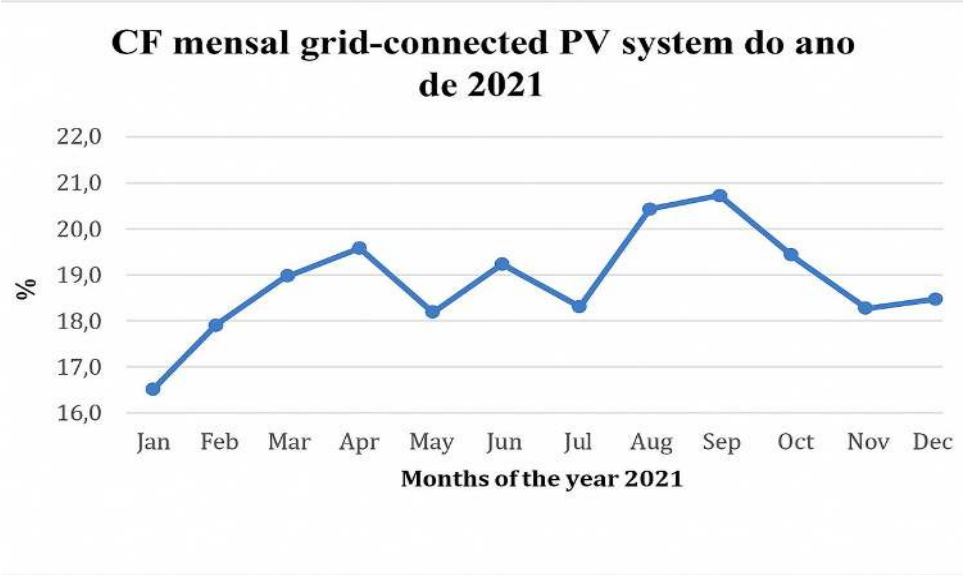
calculated with reference to the installed DC power of the modules (P_dc = 92.43 kWp), as in Eq. (9), and the annual value is the arithmetic mean of the twelve monthly CF values shown in Figure 9.

Figure 9. Monthly capacity factor of the grid-connected PV system at IFCE–Cedro Campus.



Source: Authors.

4.6 Financial analysis of the generation and consumption of IFCE-Cedro Campus

In the grid-connected PV system, the efficiency losses of the PV modules are estimated at approximately 20% over 25 years, with an annual degradation rate of about 0.8% (Souza e Penha, 2020). Over the past 5 years, energy bills have had annual increases, totaling a cumulative increase of 50.99%, with an arithmetic average of 10.19% per year (equivalent to a compound rate of 8.59% per year). Considering both the tariff escalation (10.19% per year) and the degradation (0.8% per year), the projected cash flow of the PV system grows 9.39% per year, according to Eq. (11). The financial premises of the base case are an initial investment of R$ 380,659.66, an analysis horizon of 25 years, a discount rate of 11.45% per year (historical average of the Selic rate) and savings of R$ 61,885.07 in the base year. Operation and maintenance costs and equipment replacement are not included in the

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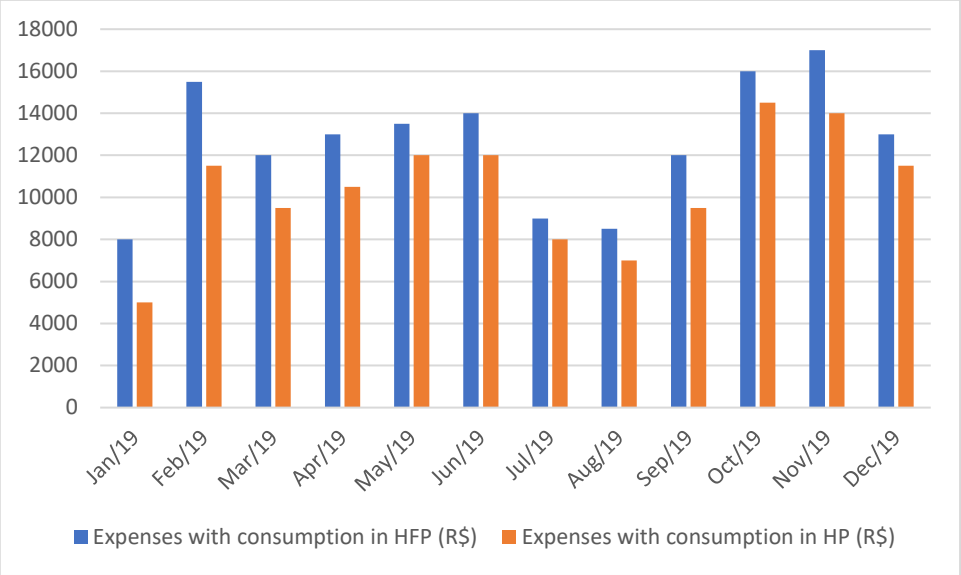
base case; the effect of operation and maintenance costs is evaluated in the sensitivity analysis (Section 4.8).

Figure 10 shows that although off-peak hours (OPH) have higher energy consumption in kWh, the costs in Brazilian Reais for both OPH and PH are similar due to the higher tariff during PH.

Figure 10. Graphical representation of electricity costs (R$) during OPH and PH.



Source: Authors.

Table 2 compares the electricity generation and consumption values. The cost is R$ 0.414 per kWh for OPH and R$ 1.91 per kWh for PH. Multiplying the generation values by the OPH tariff provides the monetary value of the generated electricity. Only the compensable active energy in the OPH is considered: no reduction in demand, sector charges or peak-hour (PH) consumption is attributed to the generation, and these items remain fully billed. Authors: complete here the composition of the R$ 0.414/kWh tariff (with or without taxes) and the compensation regime applicable to the system. Because the consumption data refer to 2019 (Section 4.1) and the generation data refer to 2021 (Section 4.2), the savings are an estimate over a reference scenario (typical 2019 consumption valued with the generation observed in 2021) and not a reduction verified in the 2021 electricity bills. In this scenario, the estimated savings are an average of R$ 5,157.08 per month, for a total of R$

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61,885.07 per year.

Table 2. Comparison between electricity generation and consumption at IFCE-Cedro Campus.

	Consumption Expenditure in OPH (R$)	Consumption Expenditure in PH (R$)	Total Consumption Expenditure (R$)	Reduction in Generation Expenses (R$)	Share of consumer spending in the uncompensated OPH (R$)
jan/19	7.928,71	4.766,85	15.724,15	4.141,388	3.787,32
fev/19	15.258,56	11.562,56	29.406,05	4.481,019	10.777,54
mar/19	12.040,16	9.430,72	24.767,26	5.108,300	6.931,86
abr/19	13.691,04	10.966,34	27.435,21	5.221,722	8.469,31
mai/19	13.973,17	12.212,73	29.622,44	5.110,748	8.862,42
jun/19	11.709,75	10.982,15	25.685,77	5.296,411	6.413,33
jul/19	8.779,33	6.368,27	18.801,04	5.252,562	3.526,76
ago/19	11.903,49	9.966,61	26.586,63	6.203,546	5.699,94
set/19	16.462,11	14.292,00	36.082,84	5.981,523	10.480,58
out/19	15.104,19	12.449,22	31.572,66	5.450,645	9.653,54
nov/19	17.903,54	14.005,37	40.686,06	4.766,917	13.136,62
dez/19	13.269,12	10.830,59	28.425,83	4.870,294	8.398,82

Source: Authors.

The total consumption expenditure in Table 2 corresponds to the amounts billed in the electricity bills of IFCE-Cedro Campus; it is higher than the sum of the OPH and PH columns because it also includes contracted/billed demand, sector charges and taxes. To calculate the amounts paid to the utility, the values generated during OPH are subtracted from the monthly consumption. Figure 11 shows the cumulative present value (CPV) over 25 years, which reaches R$ 844,287.15 at the end of the period. This value corresponds to the NPV, that is, the present value of the savings (R$ 1,224,946.81) minus the initial investment (R$ 380,659.66). The IRR is 26.72%, which is higher than the historical average of the Selic rate (11.45%), the Brazilian Central Bank's benchmark interest rate, commonly used as a reference for evaluating investments and financing costs in Brazil. Under the adopted premises,

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this indicates that the investment is financially attractive. The discounted payback period is approximately 6.6 years (about seven years), after which the cumulative present value becomes positive. To allow the NPV, IRR and payback to be reproduced, Table 3 presents the annual cash flow (nominal value, present value and cumulative present value), obtained with FC_n = 61,885.07 × 1.0939^n and a discount rate of 11.45% per year. The cash flows in Table 3 are nominal values in R$, and the payback is discounted.

Table 3. Annual cash flow of the base case (nominal value, present value and cumulative present value).

Year (n)	Nominal cash flow, FC_n (R$)	Present value (R$)	Cumulative present value (R$)
0	−380,659.66	−380,659.66	−380,659.66
1	67,696.08	60,741.22	−319,918.44
2	74,052.75	59,618.50	−260,299.95
3	81,006.30	58,516.53	−201,783.42
4	88,612.79	57,434.93	−144,348.48
5	96,933.53	56,373.33	−87,975.15
6	106,035.59	55,331.34	−32,643.81
7	115,992.33	54,308.62	21,664.81
8	126,884.01	53,304.80	74,969.61
9	138,798.42	52,319.53	127,289.15
10	151,831.59	51,352.48	178,641.63
11	166,088.58	50,403.30	229,044.92
12	181,684.30	49,471.66	278,516.59
13	198,744.45	48,557.25	327,073.84
14	217,406.56	47,659.73	374,733.57
15	237,821.03	46,778.81	421,512.38
16	260,152.43	45,914.17	467,426.55
17	284,580.74	45,065.51	512,492.06
18	311,302.87	44,232.53	556,724.59
19	340,534.21	43,414.96	600,139.55
20	372,510.37	42,612.49	642,752.04
21	407,489.10	41,824.86	684,576.89
22	445,752.32	41,051.78	725,628.68
23	487,608.47	40,293.00	765,921.67
24	533,394.90	39,548.24	805,469.91
25	583,480.68	38,817.24	844,287.15

Source: Authors. Year 0 corresponds to the initial investment (I_0 = R$ 380,659.66).

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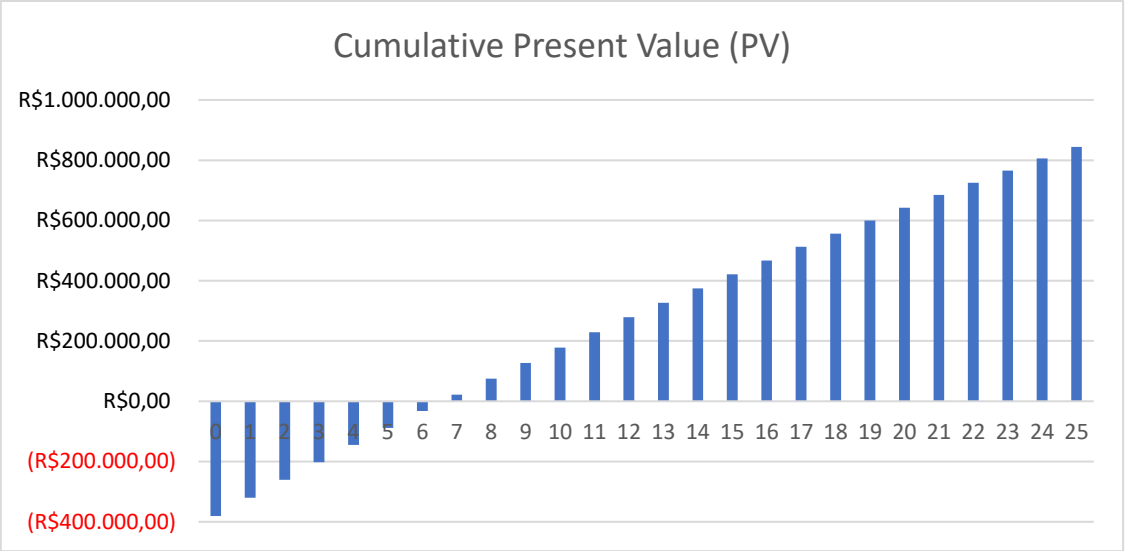
Figure 11. Cumulative present value (CPV) of the PV system over 25 years.



Source: Authors.

4.7 Levelized Cost of Energy (LCOE)

The LCOE of the grid-connected PV system was calculated, according to Eq. (10), considering an initial investment of R$ 380,659.66, a project lifetime of 25 years, an annual degradation rate of 0.8% and a discount rate of 11.45%. The numerator of Eq. (10) contains only the initial investment (operation and maintenance costs and equipment replacement were not included), and the denominator is the present value of the energy generated over the project lifetime, assuming the generation measured in 2021 (149,059.4 kWh) as the first-year generation, with an annual degradation of 0.8% and no variation in the solar resource. The present value of the energy generated over the project lifetime was estimated at 1,150,588 kWh. Therefore, the LCOE obtained was R$ 0.331/kWh (or R$ 330.85/MWh). Under these premises, this result indicates that the photovoltaic system produces electricity at a cost lower than the OPH electricity tariff charged by the utility company (R$ 0.414/kWh); the inclusion of operation and maintenance costs would increase this value.

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4.8 Sensitivity Analysis

A sensitivity analysis was performed to evaluate the robustness of the financial results, following the procedure described in Section 2.2.12. Table 4 presents the NPV, IRR and discounted payback obtained when each premise is varied individually, keeping the other premises at the base-case values (initial investment of R$ 380,659.66, discount rate of 11.45% per year, tariff adjustment of 10.19% per year, degradation of 0.8% per year, generation measured in 2021 and no operation and maintenance costs).

Table 4. Sensitivity of the NPV, IRR and discounted payback to the financial premises (one variable varied at a time).

Variable	Value	NPV (R$)	IRR (%)	Discounted payback (years)
Discount rate (per year)	8%	1,454,067	26.72	5.9
	10%	1,059,727	26.72	6.3
	11.45% (base)	844,287	26.72	6.6
	13%	661,788	26.72	7.0
	15%	480,427	26.72	7.6
Tariff adjustment (per year)	0%	93,209	14.92	12.3
	3%	224,714	18.39	9.4
	5%	343,275	20.71	8.3
	8.59%	650,967	24.87	7.0
	10.19% (base)	844,287	26.72	6.6
Annual generation	−20%	599,298	22.83	8.4
	−10%	721,792	24.80	7.4
	−5%	783,040	25.77	7.0
	0% (base)	844,287	26.72	6.6
	+5%	905,534	27.67	6.3
O&M cost (% of I_0 per year)	0.5%	828,770	26.37	6.8
	1.0%	813,253	26.02	6.9
	1.5%	797,737	25.67	7.1

Source: Authors.

In all the individual cases analyzed, the NPV remained positive and the IRR remained above the reference discount rate of 11.45%. The discount rate changes the NPV and the payback, but not the IRR, which depends only on the cash flows. The tariff adjustment was the variable with the greatest influence: with no annual adjustment, the NPV falls to approximately R$ 93 thousand, the IRR to 14.92% and

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the discounted payback increases to 12.3 years; with the compound historical rate of 8.59% per year, the NPV is R$ 650,967 and the discounted payback is 7.0 years. A 20% reduction in the annual generation reduces the NPV to R$ 599,298 (discounted payback of 8.4 years), and operation and maintenance costs of 1.5% of the investment per year reduce it to R$ 797,737 (discounted payback of 7.1 years).

Three scenarios that combine the variables were also evaluated (Table 5). The conservative scenario combines the least favorable values within the analyzed ranges (discount rate of 15% per year, tariff adjustment of 8.59% per year, generation 20% below the base case and operation and maintenance costs of 1.5% of the investment per year). The central scenario corresponds to the base case, and the optimistic scenario combines the most favorable values (discount rate of 8% per year, tariff adjustment of 10.19% per year and generation 5% above the base case, with no operation and maintenance costs).

Table 5. Conservative, central and optimistic scenarios.

Scenario	Discount rate	Tariff adjustment	Generation	O&M cost	NPV (R$)	IRR (%)	Payback (years)
Conservative	15%	8.59%	−20%	1.5%	175,912	19.93	12.6
Central (base case)	11.45%	10.19%	0%	0%	844,287	26.72	6.6
Optimistic	8%	10.19%	+5%	0%	1,545,803	27.67	5.6

Source: Authors.

Even in the conservative scenario, the NPV remained positive (R$ 175,912), with an IRR of 19.93% and a discounted payback of 12.6 years. This indicates that the conclusions about the financial feasibility of the project hold within the ranges evaluated, although the magnitude of the return depends strongly on the maintenance of tariff increases over the project lifetime.

5. Conclusion

This study analyzed the installation of a grid-connected PV system at the IFCE-Cedro Campus, which has an installed power of 92.43 kWp and a nominal power of 75 kW, classifying it as a distributed microgeneration unit.

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The performance analysis evaluated the parameters of average daily monthly generation, average monthly local irradiation, Yield, PR, and CF to provide a better analysis of the grid-connected PV system generation potential. It was found that the grid-connected PV system installed at the IFCE-Cedro Campus had an average daily annual generation of 412.57 kWh in 2021. The CF for this year reached its highest value in September at 21.11% and its lowest in January at 15.66%, with an average CF of 18.60%, which are considered satisfactory values for a grid-connected PV system.

The grid-connected PV system Yield peaked at 152.01 kWh/kWp in September and was lowest in January at 116.49 kWh/kWp. The PR was highest in June (83.10%) and lowest in January (66.39%). Performance increased between August and September due to high solar incidence and low rainfall in the region, with an average irradiance of 6.56 kWh/m²·day in September. In contrast, January had the lowest performance because it is a rainy period, with an irradiance of 5.47 kWh/m²·day.

The drop in performance in November, despite high solar irradiation, raises questions. Possible causes include losses due to high temperatures or issues with data collection, such as internet connection failures. These factors may have led to an underestimation of the average generation for the period, but the exact cause was not identified.

Based on the collected data and calculated indices, it can be concluded that the performance analysis showed that during 2021, the IFCE-Cedro Campus grid-connected PV system had adequate performance, with an average Yield of 137.77 kWh/kWp and an average PR of 74.80%, confirming that the electricity generation of the system is mostly in line with expected values.

The financial analysis of the grid-connected PV system indicated that, under the adopted premises, its installation is financially advantageous over time. The estimated savings were an average of R$ 5,157.08 per month, resulting in R$ 61,885.07 per year. These values were calculated over a reference scenario in which the typical consumption of 2019 (448,470.0 kWh, with a monthly average of 37,372.5 kWh) is valued with the generation observed in 2021, the first year of operation (149,059.4 kWh, with a monthly average of 12,421.6 kWh); therefore, they are

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estimated savings and not a reduction verified in the 2021 electricity bills. The system generated less energy than was consumed, but still resulted in significant estimated savings.

The financial analysis also indicated that the investment in the grid-connected PV system had a discounted payback of approximately 6.6 years (about seven years), with cash flows in nominal values, so that the cumulative present value remains positive during the remaining years of the 25-year horizon, considering an annual degradation of 0.8%. The NPV was R$ 844,287.15, which is already net of the initial investment of R$ 380,659.66, that is, the present value of the savings (R$ 1,224,946.81) minus the initial investment. The IRR was 26.72%, higher than the discount rate of 11.45% (Brazil's Selic rate, the Central Bank's benchmark interest rate). Additionally, the LCOE, calculated from the initial investment and the discounted energy generation, was R$ 0.331/kWh, lower than the OPH tariff of R$ 0.414/kWh, which indicates the competitiveness of photovoltaic generation compared to the electricity supplied by the utility under the adopted premises.

The sensitivity analysis showed that the NPV remained positive in all the individual cases evaluated (discount rate from 8% to 15% per year, tariff adjustment from 0% to 10.19% per year, generation from −20% to +5%, and operation and maintenance costs from 0.5% to 1.5% of the investment per year), and the IRR remained above the reference discount rate of 11.45%. The tariff adjustment was the variable with the greatest influence: without any adjustment, the NPV was approximately R$ 93 thousand, the IRR was 14.9% and the discounted payback was 12.3 years. The financial conclusions are therefore conditioned on the adopted premises, mainly on the maintenance of tariff increases over the project lifetime.

The power limitation of the inverters (clipping) and the soiling of the modules were not measured in this study, so they remain hypotheses and were not quantified. The installed DC power (92.43 kWp) is 23.24% higher than the AC nominal power of the inverters (75 kW), which indicates a potential for inverter saturation at times of high irradiance, but no operational records were available to confirm clipping losses. Likewise, soiling is only a potential loss factor; the annual degradation rate of 0.8% used in the financial model refers to the degradation of the modules and not to soiling.

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It is recommended to perform periodic cleaning of the PV modules as a good maintenance practice, without an estimate of energy gain, to monitor the operation of the inverters to evaluate their resizing, and to consider expanding the system to align generation with the institution's consumption.

It was also identified that the generation does not cover all OPH consumption, resulting in an amount the institution still needs to pay to the utility. For this reason, it would be beneficial to expand the system to achieve even more savings on the electricity expenses of the IFCE-Cedro Campus.

In conclusion, under the adopted premises and considering the sensitivity analysis, the grid-connected PV system showed to be a technically adequate and financially feasible option for the IFCE-Cedro Campus, with estimated electricity cost savings and favorable financial indicators, whose magnitude depends mainly on the tariff adjustment over the project lifetime.

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