TECHNICAL-ENERGY PERFORMANCE, OVERSIZING, AND SIMULTANEITY IN A RESIDENTIAL SOLAR POWER PLANT WITH ENPHASE MICROINVERTERS AND TRINA 705 W MODULES: A CASE STUDY IN FORTALEZA/CE

DESEMPENHO TÉCNICO-ENERGÉTICO, OVERSIZING E SIMULTANEIDADE EM UMA USINA SOLAR RESIDENCIAL COM MICROINVERSORES ENPHASE E MÓDULOS TRINA 705 W: ESTUDO DE CASO EM FORTALEZA/CE

DESEMPEÑO TÉCNICO-ENERGÉTICO, SOBREDIMENSIONAMIENTO Y SIMULTANEIDAD EN UNA PLANTA SOLAR RESIDENCIAL CON MICROINVERSORES ENPHASE Y MÓDULOS TRINA DE 705 W: ESTUDIO DE CASO EN FORTALEZA/CE

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ABSTRACT

Photovoltaic distributed generation has become established in Brazil as a relevant alternative for the energy transition, especially after the enactment of Law No. 14,300/2022, which redefined the rules of the Electric Energy Compensation System. In this context, it is important to evaluate not only the total energy generated by residential systems, but also the degree of simultaneity between generation and consumption, as well as sizing decisions (DC/AC ratio), which influence local energy use and the export of surplus energy. This study aims to analyze the technical-energy performance of a residential solar power plant with a decentralized architecture based on microinverters and high-power modules, installed in Fortaleza/CE, using real data at 15-minute intervals. The research is applied in nature, with a qualitative-quantitative approach and a case study procedure. Data from 10/19/2025 to 02/23/2026 were analyzed (generation, consumption, export, and import). The system consists of 12 Trina 705 Wp modules (8.46 kWp in direct current) and 12 Enphase IQ8P microinverters (5.7 kW in alternating current), with a DC/AC ratio of 1.48. The results indicated total generation of 5,444.03 kWh and a capacity factor of 31.34%, with occasional clipping during periods of higher irradiance (maximum observed power of 5.676 kW; 9.65% of intervals ≥ 5.6 kW). The estimated self-consumed energy was 579.11 kWh, resulting in a self-consumption rate of 10.64% and a self-sufficiency rate of 47.44%. It is concluded that the system presented consistent performance and that simultaneity is a central variable for interpreting energy utilization in residential settings, especially in projects with intentional surplus for compensation.

Keywords: Distributed Generation. Microinverters. Energy Performance. Oversizing. Simultaneity.

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RESUMO
A geração distribuída fotovoltaica consolidou-se no Brasil como alternativa relevante para a transição energética, especialmente após a promulgação da Lei nº 14.300/2022, que redefiniu regras do Sistema de Compensação de Energia Elétrica. Nesse contexto, torna-se importante avaliar não apenas a energia total gerada por sistemas residenciais, mas também o grau de simultaneidade entre geração e consumo e as decisões de dimensionamento (razão DC/AC), que influenciam o aproveitamento local e a exportação de excedentes. Este trabalho tem como objetivo analisar o desempenho técnico-energético de uma usina solar residencial com arquitetura descentralizada baseada em microinversores e módulos de alta potência, instalada em Fortaleza/CE, utilizando dados reais em intervalos de 15 minutos. A pesquisa é aplicada, com abordagem qualiquantitativa e procedimento de estudo de caso. Foram analisados dados de 19/10/2025 a 23/02/2026 (geração, consumo, exportação e importação). O sistema é composto por 12 módulos Trina de 705 Wp (8,46 kWp em corrente contínua) e 12 microinversores Enphase IQ8P (5,7 kW em corrente alternada), com razão DC/AC de 1,48. Os resultados indicaram geração total de 5.444,03 kWh e fator de capacidade de 31,34%, com clipping pontual no período de maior irradiância (potência máxima observada de 5,676 kW; 9,65% dos intervalos ≥ 5,6 kW). A energia autoconsumida estimada foi de 579,11 kWh, resultando em taxa de autoconsumo de 10,64% e taxa de autossuficiência de 47,44%. Conclui-se que o sistema apresentou desempenho consistente e que a simultaneidade é variável central para interpretação do aproveitamento energético em residências, especialmente em projetos com excedente intencional para compensação.

Palavras-chave: Geração Distribuída. Microinversores. Desempenho Energético. Oversizing. Simultaneidade.

RESUMEN
La generación distribuida fotovoltaica se ha consolidado en Brasil como una alternativa relevante para la transición energética, especialmente tras la promulgación de la Ley n.º 14.300/2022, que redefinió las reglas del Sistema de Compensación de Energía Eléctrica. En este contexto, es importante evaluar no solo la energía total generada por los sistemas residenciales, sino también el grado de simultaneidad entre generación y consumo, así como las decisiones de dimensionamiento (relación DC/AC), que influyen en el aprovechamiento local y la exportación de excedentes. Este trabajo tiene como objetivo analizar el desempeño técnico-energético de una planta solar residencial con arquitectura descentralizada basada en microinversores y módulos de alta potencia, instalada en Fortaleza/CE, utilizando datos reales en intervalos de 15 minutos. La investigación es de carácter aplicado, con enfoque cualitativo-cuantitativo y procedimiento de estudio de caso. Se analizaron datos del 19/10/2025 al 23/02/2026 (generación, consumo, exportación e importación). El sistema está compuesto por 12 módulos Trina de 705 Wp (8,46 kWp en corriente continua) y 12 microinversores Enphase IQ8P (5,7 kW en corriente alterna), con una relación DC/AC de 1,48. Los resultados indicaron una generación total de 5.444,03 kWh y un factor de capacidad del 31,34%, con clipping puntual en los períodos de mayor irradiancia (potencia máxima observada de 5,676 kW; 9,65% de los intervalos ≥ 5,6 kW). La energía autoconsumida estimada fue de 579,11 kWh, resultando en una tasa de autoconsumo del 10,64% y una tasa de autosuficiencia del 47,44%. Se concluye que el sistema presentó un desempeño consistente y que la simultaneidad es una variable central para la interpretación del aprovechamiento energético en residencias, especialmente en proyectos con excedente intencional para compensación.

Palabras clave: Generación Distribuida. Microinversores. Desempeño Energético. Sobredimensionamiento. Simultaneidad.

1 INTRODUCTION

Photovoltaic distributed generation has become one of the most relevant vectors of the energy transition in Brazil, contributing to the diversification of the energy matrix and the reduction of emissions associated with electricity production (Tolmasquim, 2003; REN21, 2024). In recent years, the fall in costs of modules, inverters, and fastening structures, combined with the greater availability of financing and the maturation of supply chains, has contributed significantly to the expansion of solar PV on a global scale (IEA, 2024; IEA-PVPS, 2024), accelerating adoption in niches such as residential rooftop systems. At the same time, normative and legal changes have redefined the form of compensation for surpluses, directly influencing the economic viability of the projects.

With Law No. 14,300/2022, which established the Legal Framework for Distributed Microgeneration and Minigeneration, new rules were established for the electricity compensation system in Brazil (Brasil, 2022; Santos; Figueira; Florian, 2024)., the logic of economic return has become more sensitive to consumption behavior simultaneous to generation, especially in systems with high exports to the grid. In this scenario, indicators such as the self-consumption rate and the self-sufficiency rate gain importance in the evaluation of the energy performance of photovoltaic systems connected to the grid (Villalva; Gazoli, 2012), as they describe how much of the energy generated is effectively used at the production site. In addition, sizing decisions, especially the DC/AC ratio, should be evaluated in conjunction with the consumer's hourly load curve, since the increase in the DC arrangement can increase the annual energy generated, but also intensify clipping episodes at peak times.

In parallel with regulatory evolution, there has been significant progress in power electronics applied to solar energy, especially in the development of more efficient inverters and decentralized conversion architectures (Pinho; Galdino, 2004). The architecture with microinverters, in which each photovoltaic module has a dedicated converter, has been adopted in scenarios that demand detailed monitoring, greater tolerance to shading, and expansion flexibility. Still, the technological choice must be supported by evidence in real operation, especially in tropical regions, where irradiance, temperature, and cloudiness regimes influence the performance of the system.

In view of the above, this work has as its general objective to analyze the technical-energy performance of a residential photovoltaic solar plant with Enphase microinverters and Trina 705 Wp high power modules, installed in Fortaleza/CE, from real monitoring data at 15-minute intervals. As specific objectives, it is sought: (i) to discuss conversion architectures applicable to residential distributed generation; (ii) present fundamentals related to DC/AC sizing and the clipping phenomenon; (iii) calculate technical performance and concurrency indicators; and (iv) report the main results observed in the analyzed period of operation, including monthly consolidation and analysis of hourly curves.

As for the structure, the work is organized into five sections: introduction; methodology; theoretical foundation; experience report in the implementation of the plant and final considerations.

2 METHODOLOGY

This research has an applied nature and a qualitative-quantitative approach, combining numerical analysis of data with technical interpretation of the results (Marconi; Lakatos, 2021). The methodological procedure adopted is the case study, appropriate to the investigation of contemporary phenomena in their real context (Yin, 2015).

The database was obtained by export from the Enphase monitoring platform (CSV file), with records at 15-minute intervals. The following fields were used: date/time, energy produced (Wh), energy consumed (Wh), energy exported (Wh) and energy imported (Wh). The period analyzed comprises 10/19/2025 to 02/23/2026.

The study unit is located in Fortaleza/CE and has a single-phase electrical connection (220V). The photovoltaic array consists of 12 Trina TSM-705NEG21C.20 modules (705 Wp each), totaling 8.46 kWp in direct current, associated with 12 Enphase IQ8P-72-2-BR microinverters, totaling 5.7 kW in alternating current, resulting in a DC/AC ratio of 1.48. The generation measurement is carried out after the microinverters (AC generation), by means of a dedicated current transformer, ensuring representativeness of the energy effectively converted and made available in the installation.

The data processing included: (i) daily and monthly consolidation; (ii) construction of average hourly curves of generation and consumption; (iii) calculation of performance indicators; and (iv) clipping analysis by evaluation of the average power at each 15-minute interval. For the indicators, the following operational definitions were adopted: self-consumed energy in each interval as the minimum between energy produced and energy consumed; self-consumption rate as the ratio of self-consumed energy to total energy generated; self-sufficiency rate as the ratio between self-consumed energy and total consumption; and capacity factor as the ratio of power generated to theoretical power if the system operated continuously at rated AC power over the period.

Table 1 presents the main parameters of the system and indicators calculated in the period analyzed.

Table 1

System parameters and calculated indicators

Parameter/Indicator	Value
Installation location	Fortaleza/CE
Period analyzed	19/10/2025 to 23/02/2026
Installed power (DC)	8.46 kWp
Rated Power (AC)	5.7 kW
DC/AC ratio	1,48
Total generation (kWh)	5.444,03
Total consumption (kWh)	1.220,61
Total Export (kWh)	4.864,92
Total import (kWh)	641,50
Estimated self-consumed energy (kWh)	579,11
Self-consumption rate	10,64%
Self-sufficiency rate	47,44%
Capacity Factor (AC)	31,34%

Source: Prepared by the author based on the Enphase report (2026).

For the construction of the theoretical framework of this study, authors who contributed significantly to the development of knowledge related to photovoltaic solar energy and distributed generation in Brazil were considered. In chronological order, Tolmasquim (2003) stands out, for the contextualization of renewable sources in national energy planning; Pinho and Galdino (2004), for the engineering fundamentals applied to photovoltaic systems; Villalva and Gazoli (2012), for the technical approach to energy conversion and integration of photovoltaic systems into the electricity grid; Nascimento and Benevides (2018), for discussions related to residential application and systems monitoring; and Santos, Figueira and Florian (2024), who analyze recent regulatory impacts and the relevance of energy simultaneity in the context after Law No. 14,300/2022.

3 THEORETICAL FOUNDATION

The theoretical foundation was organized into five topics: (i) distributed generation and regulatory framework; (ii) conversion architectures into residential photovoltaic systems; (iii) high-power photovoltaic modules; (iv) technical performance indicators; and (v) DC/AC scaling, clipping, and concurrency.

3.1 DISTRIBUTED GENERATION AND REGULATORY FRAMEWORK

The regulation of distributed generation in Brazil had as its starting point ANEEL Normative Resolution No. 482/2012 (ANEEL, 2012), which established conditions for the connection of microgeneration and minigeneration to the grid and the credit compensation mechanism.

Subsequently, the Legal Framework (Law No. 14,300/2022) consolidated rules and transitions, establishing criteria for the gradual collection of tariff components associated with the use of the network by new connections. This new arrangement makes the technical evaluation and design of the project even more dependent on the consumption profile and the level of export of surpluses.

In practical terms, residential projects can pursue two strategies: maximize local self-consumption (reducing exports) or size surplus to form energy credits to be offset in future periods and/or in other linked consumer units.

The choice affects energy indicators and the interpretation of efficiency: a low self-consumption rate may be a consequence of an intentional surplus strategy, and not necessarily of design flaws.

3.2 ARCHITECTURES AND ENERGY CONVERSION SYSTEMS IN RESIDENTIAL SOLAR POWER PLANTS

The technical configuration of residential solar plants, in turn, brings decisions that are closely linked to the performance of the system, especially in relation to energy conversion architectures. As Santos, Figueira, and Florian (2024) discuss, the choice between a central inverter, a string inverter, or a microinverter is not a matter of overall generation efficiency, but also of how the system deals with shading, localized failures, and the new regulatory requirements that emerged after Law No. 14,300/22. The comparative analysis of these architectures, therefore, is important to understand how different technological solutions adjust to the practical conditions of operation in photovoltaic systems connected to the grid.

In residential applications, Tomich Junior (2021) notes that string inverters dominate the market due to their ease of installation and lower initial price, but microinverters are becoming popular because they allow for optimized performance of each module and more detailed monitoring. This variety of options demonstrates that the system needs to be adapted to the particularities of each facility, such as available space, consumption pattern, and environmental conditions, which directly impact energy performance over time.

When dealing with solar energy for residential use, Nascimento and Benevides (2018) emphasize that, in order for the photovoltaic system to operate efficiently and reliably, it is crucial to implement energy monitoring and management strategies. Within this technological spectrum, systems with microinverters, such as Enphase, offer an alternative among the various options on the market, enabling a more detailed control of generation and the rapid detection of losses or failures. Therefore, when the Enphase system is positioned compared to other well-established solutions, it enriches the understanding of the different technological options that can be utilized in residential solar plants.

The DC/AC conversion stage is central to the quality of supply and the overall performance of the photovoltaic system (Pine; Galdino, 2004; Villalva; Gazoli, 2012). In string inverters, modules connected in series share the same operating point, which can lead to *mismatch* losses. On the other hand, the topology with microinverters performs tracking of the maximum power point (MPPT) in each module, reducing losses due to *mismatch* and partial shading (Villalva; Gazoli, 2012).

Additionally, microinverters favor granular monitoring and predictive maintenance. For operational management purposes, access to data by module allows the identification of anomalies (e.g. localized dirt, premature degradation or connection failures), reducing diagnostic time. However, designs with microinverters must consider the nominal AC power limitation per unit and the combined effect of the DC array on clipping behavior.

3.3 HIGH POWER MODULES AND WEATHER CONDITIONS

High-power modules, such as the Trina Vertex N family, utilize advanced technologies such as *n-type* cells and TOPCon architectures for increased efficiency (IEA-PVPS, 2024; TRINA SOLAR, 2024). On residential rooftops, the main benefit is higher power density, allowing higher installed powers to be achieved in limited areas. However, field performance depends on climatic variables: operating temperature, roof ventilation, albedo, and cloudiness all influence instantaneous power.

In coastal regions with a hot climate, such as Fortaleza, high temperatures can reduce the instantaneous yield of the module in relation to the standard test (STC). Still, the high annual irradiance and the greater amount of sunshine hours can sustain high annual energy production, making the place favorable to photovoltaic generation.

3.4 TECHNICAL PERFORMANCE INDICATORS

The performance analysis of grid-connected photovoltaic systems often uses consolidated energy assessment indicators (Dobos, 2014; IEC 61724-1, 2021). The specific generation (kWh/kWp) is useful for comparing different projects in different locations. The capacity factor (FC) describes the degree of utilization of the rated power over time, being influenced by irradiance, temperature, and system losses. The self-consumption rate, on the other hand, measures the fraction of energy generated that is instantly used on site, while the self-sufficiency rate expresses how much of the total consumption is supplied by self-generation.

In operational terms, simultaneity can be analyzed by hourly curves: in homes, it is common for consumption peaks to occur in the early morning and at night, when generation is low or non-existent. Thus, load displacement strategies (e.g., use of pumps, heating, recharging of vehicles or household appliances during the day) tend to increase self-consumption and reduce exports, which becomes more relevant under rules of charging for the use of the network.

3.5 DC/AC RATIO, *OVERSIZING* AND *CLIPPING*

The dimensioning of the DC/AC ratio is a relevant design decision for optimizing annual energy generation (Dobos, 2014; Villalva; Gazoli, 2012). When the DC array is higher than AC capacity, there is potential power gain at times of lower irradiance, but also greater likelihood of clipping at peaks. The intensity of the clipping depends on the local irradiance, temperature, and array profile. Thus, the evaluation should quantify the frequency of saturation and compare it with the benefit of additional production at other times.

3.6 EXPERIENCE REPORT ON THE IMPLEMENTATION OF A RESIDENTIAL SOLAR PLANT

This section describes, in the form of an experience report, the main results of the operation of the plant installed in Fortaleza/CE, based on real data obtained from the monitoring platform. The system has a generation surplus in relation to local consumption, resulting in high exports and, consequently, the formation of credits for compensation. The interpretation of the indicators is carried out considering this strategy.

In the period analyzed, the total energy generated was 5,444.03 kWh, while the total consumption recorded was 1,220.61 kWh. Exports totaled 4,864.92 kWh and imports 641.50 kWh. The estimated self-consumed energy was 579.11 kWh, which resulted in a self-consumption rate of 10.64% and a self-sufficiency rate of 47.44%.

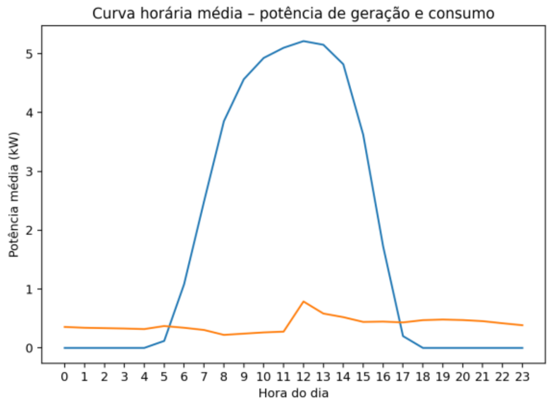
The average daily generation was 42.87 kWh/day. Considering the nominal power of 5.7 kW, the capacity factor in the period was 31.34%. These values reflect the favorable conditions of solar resources and the sizing strategy adopted.

To evaluate *clipping*, the average power was calculated at each 15-minute interval. The maximum power observed was 5.676 kW, very close to the nominal limit of the system. The frequency of intervals with power equal to or greater than 5.6 kW was 9.65%, indicating point saturation concentrated at the top of the daily curve. From a practical point of view, this behavior is expected in projects with *oversizing* and can be interpreted as evidence that the inverter was used close to the limit part of the time, without, however, eliminating the generation gain at times of intermediate irradiance.

The day with the highest generation was 01/08/2026, with a daily production of 50.25 kWh. This result is useful for illustrating typical behavior under favorable conditions, including the plateau associated with the conversion threshold. Figures 1, 2, 3, 4 and 5 illustrate all the calculations developed.

Figure 1

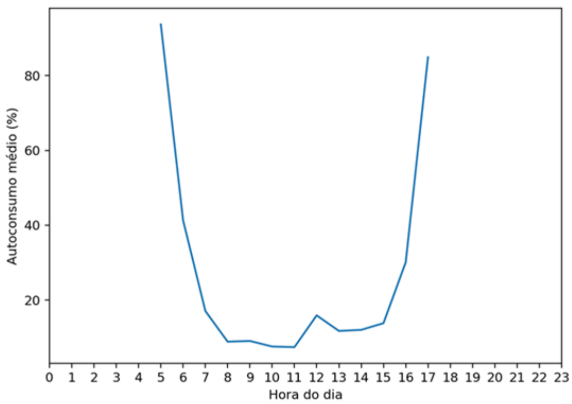
Average hourly curve of generation and consumption power



Source: Prepared by the author from the Enphase report (2026).

Figure 2

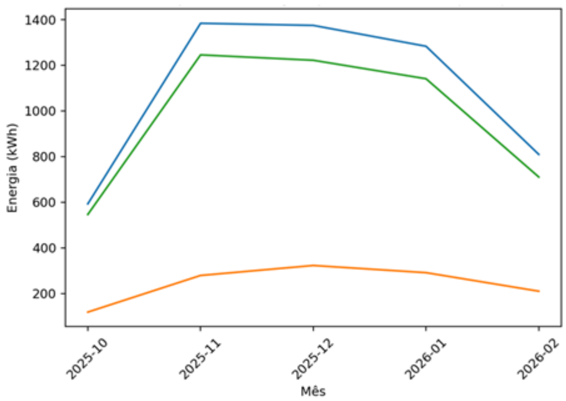
Average hourly rate of self-consumption



Source: Prepared by the author from the Enphase report (2026).

Figure 3

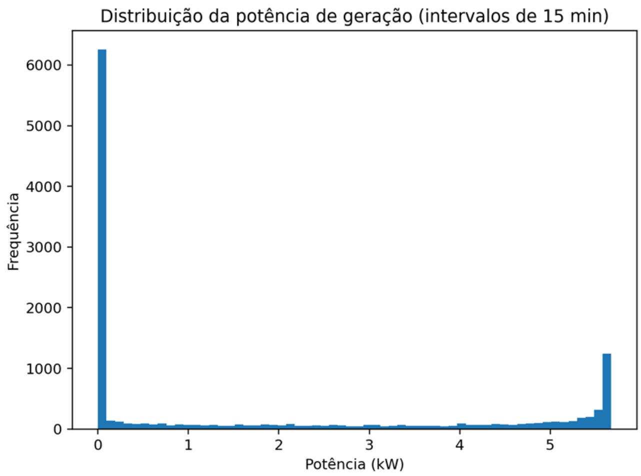
Monthly consolidation of generation, consumption and exports



Source: Prepared by the author from the Enphase report (2026).

Figure 4

Generation power distribution (15-minute intervals)



Source: Prepared by the author from the Enphase report (2026).

Figure 5

Generation profile on the day of highest production

Source: Prepared by the author from the Enphase report (2026).

Table 2 shows the monthly energy consolidation (kWh) in the period analyzed.

Table 2

Monthly Energy Consolidation

Month	Generation	Consumption	Export	Import
2025-10	592,69	118,31	546,24	71,87
2025-11	1383,89	278,88	1245,52	140,51
2025-12	1374,71	322,5	1221,92	169,7
2026-01	1283,29	291,07	1140,9	148,69
2026-02	809,46	209,85	710,35	110,73

Source: Prepared by the author from the Enphase report (2026).

The hourly analysis indicates that self-consumption is maximized in the periods of lower irradiance (morning and late afternoon), when generation approaches consumption. In the central period of the day, the surplus is expressive, resulting in high exports. This result is consistent with the project's strategy: the plant was sized to generate more than local consumption, allowing compensation for the surplus in another consumer unit, in addition to reducing dependence on grid energy at times of solar availability.

In terms of regulatory interpretation, the scenario reinforces that residential projects should be analyzed considering: (i) load profile; (ii) compensation policy; (iii) possibility of consumption management; and (iv) tariff structure. In the case analyzed, high exports are desired from the point of view of energy credit, but it reduces the rate of local self-consumption, which does not represent, in itself, low technical performance.

4 FINAL CONSIDERATIONS

The present work evaluated the technical-energy performance of a residential photovoltaic plant with microinverters and high-power modules, using real data at 15-minute intervals. The approach allowed calculating performance indicators, analyzing hourly curves and quantifying clipping, providing practical evidence for sizing decisions in residential distributed generation.

In the period analyzed, the system presented a total generation of 5,444.03 kWh and a capacity factor of 31.34%, indicating high performance by residential standards. The DC/AC ratio of 1.48 was technically adequate to the local conditions, with punctual and non-dominant clipping. The local self-consumption rate was 10.64% and the self-sufficiency rate was 47.44%, values influenced by the strategy of intentional surplus.

The results show that the simultaneity between generation and consumption should be interpreted in the light of the project's objective and regulatory rules. When the purpose includes compensation in other consumer units, high exports are part of the strategy. Even so, in contexts of higher charges for network use, increasing self-consumption by load and/or storage management can become relevant for economic optimization.

As limitations, it is noteworthy that the analyzed period does not include a complete annual cycle, which restricts conclusions about annual seasonality. In addition, local measurements of irradiance and module temperature were not incorporated, which makes it impossible to calculate indicators such as Performance Ratio. As future works, it is recommended: (i) to extend the horizon to 12 months; (ii) integrate meteorological data; (iii) evaluate tariff and economic scenarios; (iv) simulate load displacement strategies; and (v) analyze impacts of possible insertion of storage.

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