Mitigating thermal derating in photovoltaic inverters: insights from a real grid-connected system

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Abstract

Brazil stands out for having a predominantly sustainable electricity matrix, with solar photovoltaic energy playing an increasingly significant role. In this context, Grid-Connected Photovoltaic Systems (GCPS) have been expanding widely, including in public institutions. This study presents an operational analysis of the GCPS at the Center for Technology and Geosciences (CTG) of the Federal University of Pernambuco (UFPE). It was found that the inverters operate at temperatures averaging 30 °C above the manufacturer's recommended limit. Based on this, experimental tests and a frequency-of-occurrence study were carried out to investigate performance losses due to thermal stress. Real generation data were compared with PVSyst simulations, indicating deviations over 17%. The results support corrective actions and operational improvements in the system.

Keywords: Photovoltaic System, Inverter Temperature, Performance Analysis, Thermal Stress, Thermal Power Derating, Distributed Generation.

1. Introduction

Brazil stands out globally for having an electricity matrix predominantly composed of renewable sources, especially hydropower. According to the 2025 National Energy Balance (BEN), which reports on data from 2024, over 85% of Brazil's electricity generation comes from renewable sources, with a total electricity supply of 762.9 TWh. Among these, solar photovoltaic (PV) energy plays an increasingly important role, reaching 70.7 TWh of generated energy and 48.5 MW of installed capacity—an 28.1% growth compared to the previous year.

Nevertheless, Brazil's energy infrastructure remains highly centralized, with large-scale generation facilities and extensive transmission lines, which contributed to almost 10.0% energy loss in 2024 alone (BEN, 2025). Combined with declining water levels in hydropower reservoirs and the aging of hydroelectric facilities, this centralized model increases energy vulnerability.

Distributed Generation (DG), especially through photovoltaic systems, emerges as a promising alternative. Since the introduction of net metering regulations in 2012, the country has seen over 1.78 million solar micro and mini-generation systems installed. Although PV generation currently represents only 9.3% of the national matrix, it plays a key role in the energy transition due to Brazil's high solar potential—especially in the Northeast, where irradiation levels are among the highest in the world (BEN, 2025).

While adequate solar resources and reliable equipment are fundamental, optimal system performance also depends on proper design and operational conditions. Inverters are critical components whose efficiency and lifespan are significantly affected by operating temperature. Undersizing inverters, a common strategy to reduce system costs, can lead to prolonged operation under stress, increasing internal temperatures and triggering power limitation modes that reduce energy output.

The efficiency and performance of Grid-Connected Photovoltaic Systems (GCPS) are influenced by several factors, including the proper sizing of inverters and their operating temperature. Since the commercially dominant crystalline silicon technology is characterized by a significant reduction in power output as operating

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temperature increases, the nominal power at Standard Test Conditions (STC) is rarely achieved throughout the year. This typically leads to an increase in the photovoltaic generator capacity relative to the inverter power as a strategy to enhance the system's annual energy yield (Paiva et al., 2016).

The Inverter Sizing Factor (ISF) was central to the analysis. ISF represents the ratio between the inverter's nominal power and the PV array's rated power and the concept, defined in Eq. (1). It establishes the relationship between the power of the inverter and the power of the PV generator under STC (Scarabelot et al., 2021 apud Rampinelli et al., 2007).

$$ISF = \frac{P_{INV}}{P_{PV}} \quad \text{(eq. 1)}$$

Where P_{INV} is the nominal power of the inverter and P_{PV} is the generator power in STC. An inadequately selected ISF can lead to power clipping or inefficient operation under high irradiance conditions. The analysis of the ISF is an important aspect of GCPS design because inverter undersizing can reduce the cost of generated energy, thus improving the economic feasibility of such systems. If improperly sized, PV system inverters operate under overload conditions. When high temperatures are reached, inverter operation is limited, reducing output power and leading to generation losses. This process is known as thermal derating. According to Lima et al. (2023), power reduction due to temperature is not a trivial issue, as the inverter's ability to limit its output directly affects system performance. However, this power limitation is essential for protecting the converter and excessive undersizing exposes the inverter to prolonged periods of higher operating temperatures, which may reduce the equipment's lifespan (Roversi and Rampinelli, 2020).

Beyond thermal stress, an inadequately chosen ISF can cause the inverter to reach its maximum operational temperature more frequently, activating thermal derating mechanisms that limit output power. This process, while protective, results in the inverter reducing its AC output to prevent overheating, consequently wasting available solar energy that could otherwise be converted into electricity. Repeated thermal derating events can thus compromise both the energy yield and the long-term performance of the PV system, making this an important parameter for system optimization and design in warm climates. Furthermore, studies demonstrate that thermal stress in solar inverter components reduces their lifetime (Menezes et al. 2025, apud Sangwongwanich et al, 2018 and Choi, 2020), reinforcing the importance of managing operating temperatures.

Despite the relevance of this issue, few studies in literature have evaluated this topic, especially under tropical climatic conditions. Most existing analyses are based on laboratory experiments or manufacturer models that do not fully reflect real-world environmental interactions. This gap underscores the need for field-based investigations that assess how environmental and design factors, such as inverter installation conditions, ISF selection or need of forced ventilation, affect the occurrence of derating and energy losses.

To address this gap, this study presents an operational analysis of a real grid-connected PV system installed at the Federal University of Pernambuco (UFPE), located in Brazil's tropical Northeast region. The research quantifies the frequency of thermal derating events, evaluates the influence of high operating temperatures on inverter performance, and explores practical mitigation strategies, including forced ventilation and design adjustments to the ISF. By combining monitored operational data with field experiments, this study provides original insights into the thermal behavior of inverters under real tropical conditions and contributes to improving the performance and reliability of PV systems operating in similar environments.

2. Methodology

The methodology adopted in this study was structured into four main phases: collection of operational data, comparative analysis of energy generation, thermal assessment of the inverters, and performance simulations. Initially, real operational data were collected from the Grid-Connected Photovoltaic System (GCPS) installed at the Center for Technology and Geosciences (CTG) of the Federal University of Pernambuco (UFPE). The system consists of 792 polycrystalline silicon (p-Si) photovoltaic modules, each rated at 345 Wp, resulting in a total installed DC capacity of 273.24 kWp. The array is connected to three 60 kW string inverters, yielding a combined nominal AC power of 180 kW. The PV modules are mounted with a 10° tilt angle facing north, corresponding to the optimal inclination for local latitude and an azimuth of -84.3°.

Figure 1: General view of the photovoltaic array composed of 792 p-Si modules (345 Wp each), illustrating partial cloud shading and the group of three 60 kW inverters (Silva et al., 2024).

The data used in this study were obtained from two independent acquisition systems, each with distinct temporal resolutions. The first, developed specifically for this research, recorded parameters including plane-of-array irradiance, PV module temperature, inverter temperature, and indoor ambient temperature near the inverters, with measurements taken every minute. In parallel, data from the inverter manufacturer's monitoring platform were acquired, including solar radiation, ambient temperature, active power, generated energy, line voltage and current, voltage and current per MPPT, power factor, and inverter internal temperature, with a temporal resolution of one record every ten minutes.

To evaluate the actual performance of the GCPS installed at CTG/UFPE, a comparative analysis was conducted between the measured generation data and the simulated generation results obtained through the PVSyst software (version 7.3). The simulation was configured using the same technical parameters of the real system as described above. The local horizon and shading conditions were also incorporated to ensure accurate representation of the physical configuration.

All datasets were exported in CSV format, and subsequent data qualification and synchronization were carried out using MATLAB, Python, and Microsoft Excel routines developed to filter and analyze the data. Global tests are applied to the entire time series to evaluate whether it presents inconsistencies such as discontinuities, missing data, gaps, or errors in date and time records (Petribú et al, 2017). Data validation included removing missing records, unrealistic irradiance spikes (>1200 W/m²), and negative power readings. Only data corresponding to inverter operation under normal grid-tied conditions were retained for analysis. The processing routines involved filtering outliers and inconsistent measurements, aligning time bases between both systems, and preparing the data for comparative and statistical analysis, according to Silva et al., 2024.

The analysis covered the period from August 2022 to July 2023, allowing for a comprehensive evaluation of the system's annual behavior. The Typical Meteorological Year (TMY) data used for the simulation were obtained as detailed in Miranda et al., 2021, based on locally measured irradiance and temperature series. The TMY was used as an input to generate the expected annual energy output and to serve as a reference for comparison with the measured production. The comparison between the real energy generation produced by the system and the simulation are shown in Table 1.

Table 1: Measured and Estimated Energy Generation (2022).

	Jan	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Measured Generation (MWh)	34.39	26.49	21.89	28.36	25.23	24.42	26.63	30.89	32.00	34.48	33.45	35.78
Estimated generation – PVSyst (MWh)	36.26	36.48	34.99	32.09	24.97	26.92	30.17	32.17	35.95	39.17	39.83	38.98
Difference (%)	5.44	37.71	59.84	13.15	1.03	10.24	13.29	4.14	12.34	13.60	19.07	8.94

The contrast between the simulated and real energy outputs is evident. Over the course of one year, the measured energy yield was approximately 17% lower than predicted, which motivated an in-depth investigation into the underlying causes of this discrepancy.

Upon identifying this discrepancy, an in-depth analysis was carried out on the operating temperature of the inverters. The manufacture's recommended limit is 60°C and based on records from the monitoring system, it was observed that the inverters operated reaching internal temperatures up to 30 °C above the limit on many occasions. The inverters were installed indoors, within a confined technical room with limited air circulation and no forced ventilation, factors that likely contributed to heat accumulation during peak irradiance periods. A statistical analysis was conducted on the frequency of these elevated temperatures and the correlation between thermal peaks and the possible occurrence of thermal derating, which reduces the inverter's output power as a protective mechanism.

Finally, additional tests and simulations were conducted to investigate potential mitigation strategies for the excessive operating temperatures. These tests included analysis of the installation environment, verification of natural ventilation, partial shading, and adjustments to the Inverter Sizing Factor (ISF). The simulations aimed to identify more efficient configurations between the PV array capacity and the inverter power rating, in order to minimize thermal derating occurrences and consequently increase the system's energy performance. This comprehensive set of analyses contributed to the identification of operational issues and the proposal of improvements for the GCPS at CTG/UFPE. Unlike previous studies conducted under laboratory conditions, this work analyzes inverter derating behavior under real tropical field conditions, providing practical insight into temperature-performance relationships.

3. Results and discussion

3.1. Inverter Sizing Factor Analysis

In the CTG/UFPE photovoltaic system, the calculated ISF was 0.66, which characterizes a significantly undersized relative to the installed DC capacity. In such conditions, the inverter operates for longer periods close to its maximum AC output, especially during high irradiance hours. This constant high-load operation results in greater heat generation within the power electronics, which increases the inverter's internal temperature and consequently the likelihood of thermal derating events.

A partial reduction in electrical power protects semiconductor components that are sensitive to high temperatures, providing a gradual reduction in temperature, and only at critical temperatures can the inverter shut down (Scarabelot et al, 2021 apud Rampinelli et al. 2016; Solar Technology, 2019). This behavior is consistent with the field data collected throughout the monitoring period. The temperature records frequently exceeded 90 °C, approximately 30 °C above the manufacturer's recommended limit (60 °C), confirming that the inverters were subject to persistent thermal stress. The high operational temperature triggered the inverter's internal protection routines, reducing power output intermittently to prevent damage, a clear manifestation of thermal derating.

3.2. Thermal Performance of the Inverters

An important operational aspect identified in the system was the temperature behavior of the inverters during normal operation. According to the manufacturer's datasheet, the maximum operating temperature is 60 °C, with a 10% tolerance, allowing up to 66 °C. However, under high solar irradiance and elevated ambient temperatures, the supervisory platform recorded internal inverter temperatures reaching up to 90 °C, well above the recommended limit, suggesting that the originally installed passive ventilation system was insufficient to dissipate the internally generated heat.

The inverter reduces its output power at certain temperatures, a process known as thermal power derating. The energy supply from the photovoltaic inverter is restored once the equipment returns to safe operating temperatures (Lima et al., 2023). In other words, when the temperature exceeds the operational range supported by the system, the inverter shuts down or reduces the processed AC power to prevent internal damage caused by overheating, significantly reducing energy production. In severe cases, however, the inverter may temporarily shut down, leading to measurable losses in daily energy yield.

Table 2 presents the frequency of overtemperature occurrences (f_{oc}) throughout the monitoring period (5:00 a.m. – 5:00 p.m.) for each inverter. The parameter f_{oc} represents the quantity of temperature readings exceeding the datasheet limit of 66 °C and the percentage is relative to the total number of measurements for that month. The data were sampled every 15 minutes by the inverter monitoring system. As an example, during august/22, a total of 1,470 temperature reading were recorded for the inverter 1, among which 584 exceeded the specified temperature limit. Thus f_{oc} corresponds to 39.73% of the total measurements collected.

Table 2: Overtemperature occurrence frequency in the operation of the CTG/UFPE GCPS inverters

	Inverter 1		Inverter 2		Inverter 3	
	f_{Oc}	Percentage	f_{Oc}	Percentage	f_{Oc}	Percentage
aug/22	584	39.73%	555	37.76%	481	32.72%
sept/22	627	46.41%	621	45.97%	520	38.49%
oct/22	730	51.26%	707	49.65%	630	44.24%
nov/22	660	52.09%	650	51. 30%	588	46.41%
dec/22	645	58.00%	641	57.64%	586	52.70
jan/23	728	58.38%	720	57.74%	638	51.16%
feb/23	693	55.57%	686	55.01%	598	47.96%
mar/23	587	43.81%	546	40.75%	469	35.00%
apr/23	506	39.91%	494	38.96%	429	33.89%
may/23	439	35.26%	442	35.50%	368	29.56%
june/23	306	22.01%	303	21.80%	229	16.47%
july/23	380	28.15%	366	27.11%	273	20.22%

Across the 12-month period, several months recorded overtemperature frequencies greater than 35%, indicating that the inverters operated under thermal stress for a significant portion of their operational hours. This pattern was consistent among all three inverters, confirming a systemic rather than isolated condition. The results showed that in certain months, more than 50% of the recorded temperatures remained above the acceptable limit, especially between 10 a.m. and 2 p.m.

Figure 2 presents a bar chart illustrating the monthly average operating temperatures of the inverters over a 12-month period. The dark blue bars represent temperatures within the operating limit recommended by the manufacturer (66 °C), while the red segments indicate the extent to which the monthly average temperatures exceeded this limit. The green line visually highlights the maximum allowable temperature threshold. It can be observed that, in several months — particularly between January and April — the average values exceeded the limit, demonstrating the recurrence of inverter overheating. This visualization reinforces the analysis that the original passive ventilation system was inadequate to maintain the equipment within acceptable thermal conditions.

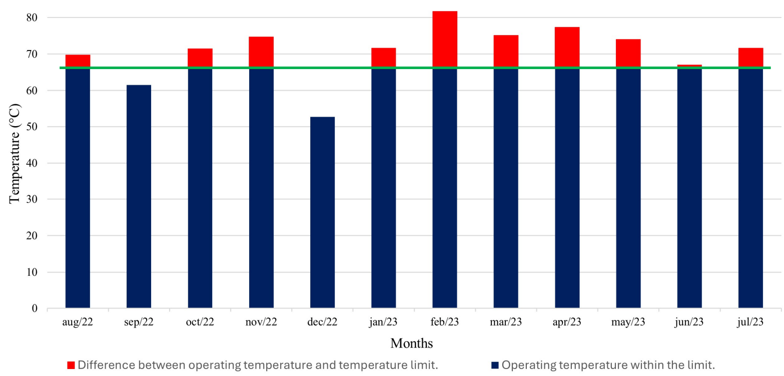


Figure 2: Monthly average operating temperatures of the inverters with indication of the limit temperature.

The inverters were mounted on a west-facing wall exposed to direct solar radiation during the afternoon and located in a confined room with limited air circulation. These conditions are unfavorable for natural convection and explain the sustained high internal temperatures observed. According to manufacturer guidelines, inverters should be installed in well-ventilated environments and protected from direct sunlight — conditions not fully met in the CTG/UFPE system.

Figure 3: Inverter's installation site in the CTG/UFPE system (Silva et al., 2024)**.**

As discussed in Lima et al. (2023), is important to analyze the influence of the inverter's operating temperatures on its performance. Therefore, to more effectively monitor the temperature variations, five additional LM-35 sensors were positioned: two on inverter 1, two on inverter 2 and one to measure the room's ambient temperature, Figure 4. Furthermore, a fan was aimed at the inverter 1 to force ventilation and observe if a decrease in operating temperature occurred. The fan was installed using an EKAZA smart plug, which allowed its operation to be controlled via a simple mobile application as shown in Figure 5. It is important to note that the dan was positioned to respect the equipment's natural convection flow, as shown in Figure 6.

Figure 4: New sensors installation (Silva et al., 2024).

Figure 5: Fan positioning.

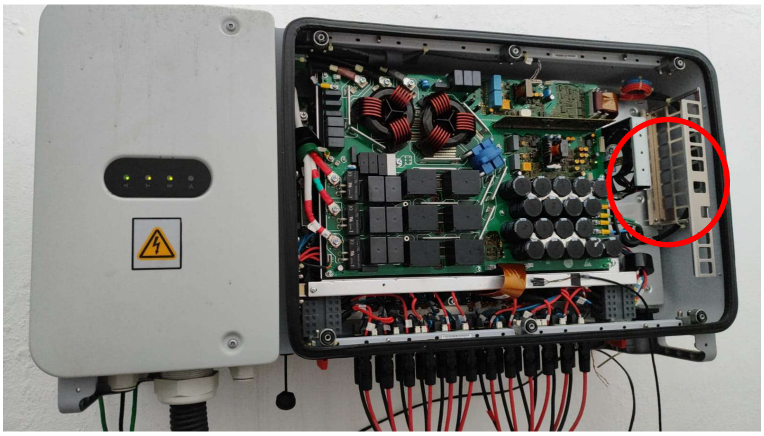


Figure 6: Internal view of the inverter, showing the cooler.

Subsequent measurements from November 2023 to January 2024 (Table 3) confirmed that the frequency of overtemperature events decreased notably in the ventilated inverter — from around 50% to approximately 33%, representing a 30% reduction in thermal stress. Nevertheless, the total energy yield of the ventilated inverter remained slightly below that of the non-ventilated unit.

It is also worth noting that the daily power output curves of the inverters were analyzed throughout the study period (although not presented in this paper). The analysis revealed no evidence of prolonged intervals with fixed or limited AC power below the inverter's nominal rating, which would typically indicate active thermal derating. This finding reinforces that the selected ISF of 0.66 and the installation environment were not the direct causes of performance reduction.

The methodology applied in this work can be replicated by other researchers or engineers investigating PV systems whose Performance Ratio (PR) is below expectations, particularly in cases involving low ISF values or inverters installed in environments with insufficient ventilation. By correlating inverter temperature, power output, and operating frequency data, this approach enables the verification of whether thermal derating is truly occurring, thus facilitating accurate diagnosis of underperforming PV systems.

Based on the data presented in Table 3, the positive impact of reducing the occurrence of temperatures above the inverter's acceptable limit becomes evident. However, the energy production of Inverter 1 remained lower than that of Inverter 2. Figure 7 complements this analysis by presenting three graphs showing the ratio between the energy generation of Inverters 1 and 2. Values below 100% indicate that, even without ventilation, Inverter 2's generation was slightly higher than that of the ventilated inverter, while on certain days, Inverter 1 managed to surpass Inverter 2 in terms of energy production. It is also worth noting that some days show missing generation records due to communication issues between the monitoring system and the local internet network.

	Inverter 1			**Inverter 2**		
	Generation (kWh)	**Temperature above the datasheet limit (60°C)**		**Generation (kWh)**	**Temperature above the datasheet limit (60°C)**	
		f_{OC}	Percentage		f_{OC}	Percentage
nov/23*	3,679.03	171	38.95%	3,745.31	217	49.54%
dec/23**	11,379.19	443	31,42%	11,650.75	636	45.11%
jan/24**	11,845.91	399	33,00%	12,087.17	538	44.54%

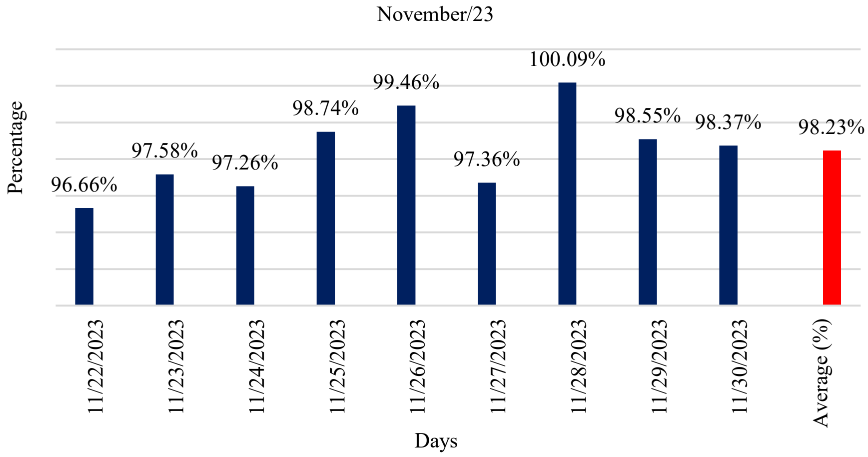
*In Nov/23 the period considered of data acquisition was between 11/22/23 - 11/30/23.

** In a few days the Generation wasn't registered due to communication failure among the monitoring system and the local internet network.

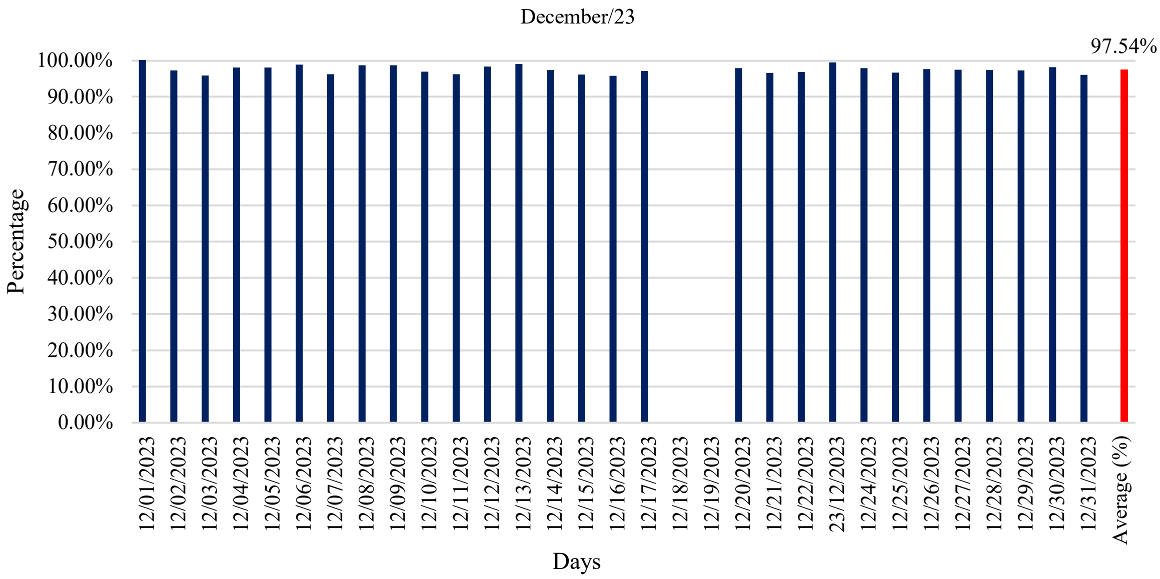
Table 3: Energy generation and overtemperature occurrence after forced ventilation installation.

Figure 7: Graphs showing the ratio between the generations of Inverter 1 and 2. Period: Nov/23 to Jan/24.

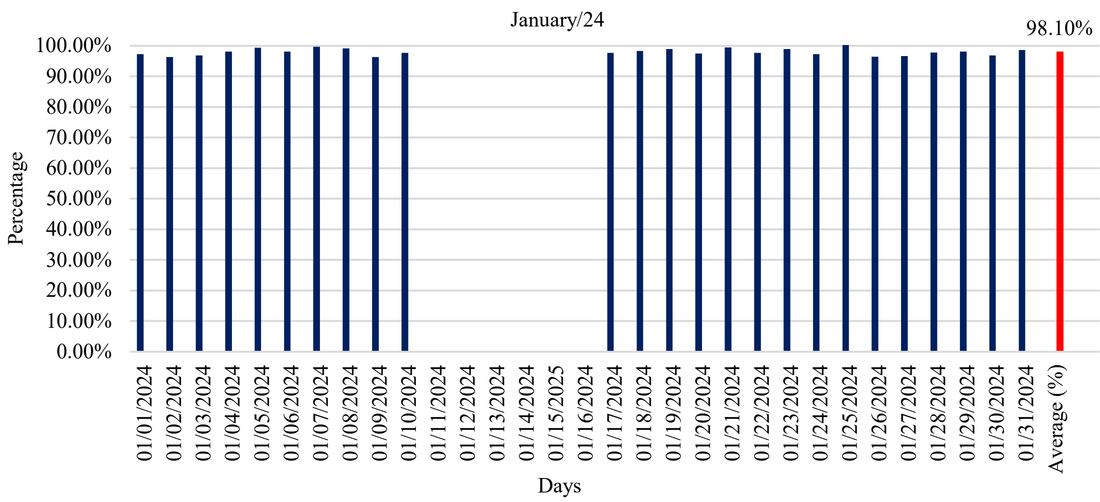
a)



b)

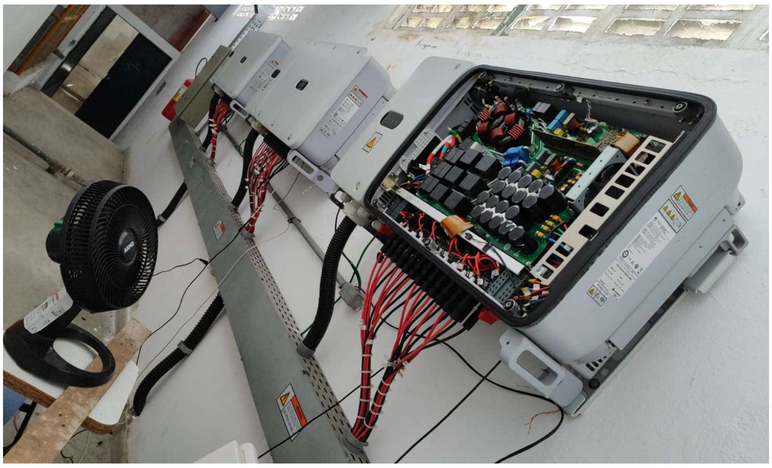


c)



In a final test, Inverter 1 was operated with its protective cover removed and continuous forced ventilation, as shown in Figure 8. This configuration effectively eliminated all overtemperature occurrences (Table 4), reducing the operating temperature by up to 30 °C compared to the control unit. However, the energy generation pattern remained largely unchanged, suggesting that while ventilation efficiently reduced temperature, thermal derating was not the main limiting factor in energy production.

Figure 8: Inverter 1 operating with protective cover removed and continuous forced ventilation.



	Inverter 1			Inverter 2		
	Generation (kWh)	Temperature above the datasheet limit (60°C)		Generation (kWh)	Temperature above the datasheet limit (60°C)	
		f_{Oc}	Percentage		f_{Oc}	Percentage
02/08/2024	397.22	0	0,00%	404.97	22	44.90%
02/09/2024	340.22	0	0,00%	349.59	16	32.65%
02/10/2024	340.28	0	0,00%	346.44	14	28.57%
02/11/2024	367.31	0	0,00%	376.25	20	40.82%
02/12/2024	398.41	0	0,00%	405.31	24	48.98%
02/13/2024	385.81	0	0,00%	394.56	23	46.94%
02/14/2024	411.78	0	0,00%	415.16	22	44.90%

Table 4: Generation and frequency of temperatures exceeding the limit after the cover was opened.

The energy generation curves of both inverters during the week in which Inverter 1 operated without its protective cover can be seen in Figure 9. When analyzing these data together with the frequency of temperature occurrences above the datasheet limit, as shown in Table 4, it is evident that, despite temperature reductions of up to 30 °C in some cases, the overall energy generation pattern remained unchanged. An interesting aspect to note is that the frequency of overtemperature occurrences dropped to zero on all days when the inverter operated with the protective cover open, confirming the effectiveness of ventilation in reducing the inverter's operating temperature.

Figure 9: Energy Generation with protective cover removed and continuous forced ventilation.

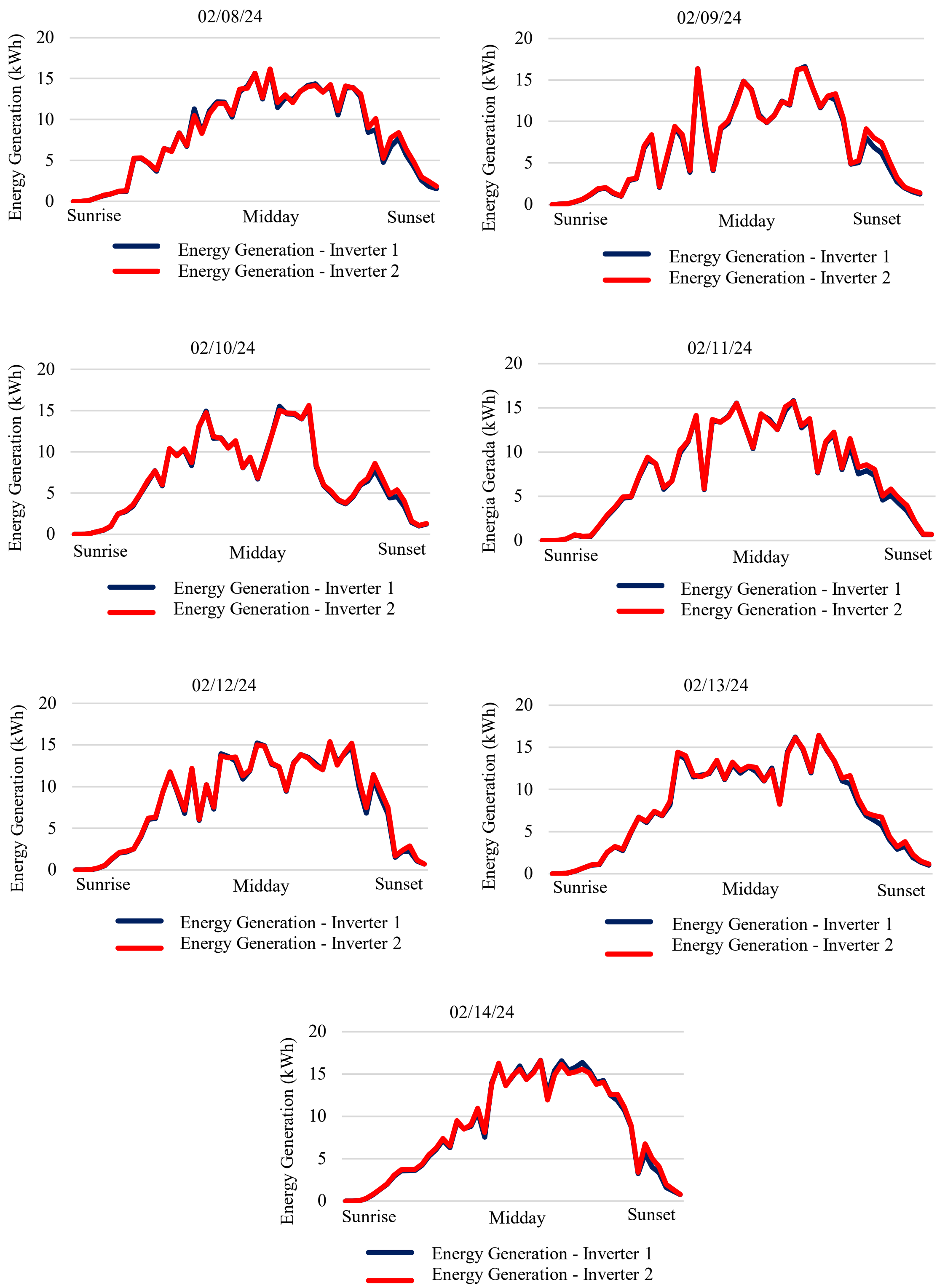


Figure 9 shows the comparison between Inverters 1 and 2 for the same operating period in the years 2023 and 2024. The average generation ratio improved by only 2.5% following the ventilation intervention, indicating that the root cause of reduced output may lie in other internal limitations, such as inverter efficiency, that is strongly affected by its operating temperature, MPPT tracking errors, or internal control thresholds not publicly documented by the manufacturer.

These insights underscore the importance of integrated thermal and electrical diagnostics in PV system analysis. The proposed monitoring strategy — combining manufacturer data with independent temperature sensors — proved effective for identifying thermal anomalies and evaluating mitigation strategies under real tropical field conditions, a context still underrepresented in the scientific literature.

4. Conclusions

The analysis revealed that the actual energy generation was approximately 14% lower than the expected output estimated through PVSyst simulations, corresponding to an annual energy deficit of about 50 MWh. Over a projected lifetime of 25 years, this difference represents a potential financial loss of roughly R$ 1,375,000.00. Subsequent analyses indicated that this discrepancy was not caused by issues on the DC side of the system, but rather by operational and thermal conditions affecting the inverters.

The inverters frequently operated above the manufacturer's recommended temperature limit (66 °C), with occurrences of overtemperature events exceeding 35% of the recorded data in several months. This behavior is consistent with the low ISF adopted in the project — a configuration that, while improving annual yield under moderate conditions, leads to higher internal heating and a greater probability of thermal derating.

To mitigate these effects, forced ventilation was implemented on one of the inverter units. The results demonstrated a clear reduction in the frequency of overtemperature occurrences, from an average of 19 daily events before ventilation to 11 after its installation. When the inverter operated with its protective cover open, the occurrence rate dropped to zero. Although the temperature reduction did not result in a substantial increase in instantaneous power generation, a 2.5% average improvement in energy yield was observed, representing an estimated lifetime financial benefit of approximately R$ 221,000.

Even though no clear evidence of thermal derating was observed in the analyzed PV system, the high frequency of inverter temperatures exceeding the nominal operating limit indicates persistent thermal stress conditions. Such exposure, if sustained over time, can accelerate material degradation, reduce component reliability, and increase the likelihood of premature inverter failure. Therefore, these results emphasize the importance of maintaining proper thermal conditions, either through forced ventilation or a fully air-conditioned environment to ensure stable operation and prolong inverter lifespan.

These findings confirm that high operating temperatures can considerably affect inverter performance, reliability, and system efficiency — particularly in tropical climates where ambient temperatures are naturally high. Furthermore, the study underscores that undersized inverters, though economically attractive, require adequate thermal management to prevent excessive temperature rise and performance degradation over time.

Finally, it is important to note that this study was limited by the restricted monitoring period during forced ventilation tests and the lack of access to internal inverter control data, which may conceal specific design or firmware-related power limitations. Nevertheless, the results obtained demonstrate the relevance of thermal analysis in photovoltaic system operation and provide a solid foundation for future studies on inverter behavior and performance optimization under real tropical conditions.

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