# PERFORMANCE ANALYSIS OF STANDALONE PHOTOVOLTAIC SYSTEMS (SIGFIS) IN THE BRAZILIAN AMAZON

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**Abstract**

The depletion of fossil fuels and the ongoing environmental crises make the transition to renewable sources indispensable. Solar energy stands out for its wide availability and technological advances. Many families in remote areas of the Brazilian Legal Amazon still lack access to the electrical grid. To address this issue, the Federal Government created the Mais Luz para a Amazônia (MLA) Program, which installs Individual Photovoltaic Generation Systems with Intermittent Sources (SIGFIs) capable of autonomous operation. The variability of solar irradiation requires the proper sizing of the batteries that compose the SIGFI, while logistics and maintenance in isolated areas remain challenging. This study evaluates the performance of three 80 kWh/month SIGFIs under different consumption and environmental conditions. One of the systems showed excessive demand and recurrent failures until December 2024. After user training in January 2025 covering rational energy use and load management monitoring indicated significant improvement and operational stability. The results demonstrate that user training and awareness are decisive for the reliability and durability of isolated photovoltaic systems, emphasizing that community engagement is as vital as equipment quality for the sustainability of SIGFIs in the Legal Amazon.

*Keywords: Energy storage; SIGFI; User training; Isolated system; Operational performance; Brazilian Legal Amazon.*

## 1. Introduction

Currently, there is a growing pursuit of alternative sources of electrical energy, both for isolated areas and for interconnected systems. This pursuit is driven by the need to diversify the energy matrix, reduce dependence on fossil fuels, and meet increasing electricity demands with lower environmental impact (Doctors & Kelman, 2017). According to the International Energy Agency (IEA, 2025), global energy demand grew by 2.2% in 2024, a rate significantly faster than the annual average of 1.3% observed between 2013 and 2023. The 2025 report "Tracking SDG 7: The Energy Progress Report" states that approximately 92% of the world's population already has access to electricity; however, around 666 million people still lack basic access, with most concentrated in Sub-Saharan Africa and the countries that make up the Amazon rainforest region (IEA, 2025b).

In the Brazilian Legal Amazon, as noted by Rabelo (2024), around 990,000 people remain without access to the public electricity service, representing 3.5% of the regional population. To provide electricity access to these populations, one off-grid system option is the installation of Individual Electrical Energy Generation Systems with Intermittent Sources (SIGFI) (Jannuzzi, Varella & Gomes, 2009). According to the study, SIGFI represents a strategic option to deliver electricity to isolated populations, reducing inequalities in access and promoting the democratization of energy use.

According to the Renewables 2020 Global Status Report (REN21, 2020), off-grid solar systems have already become consolidated and effective alternatives for meeting energy generation and distribution needs in communities without access to conventional electrical networks. It is estimated that approximately 493 million people make use of such solar technologies, either as their primary source of electricity, as a backup solution, or for productive applications (Lighting Global, 2022).

Despite this potential, vast areas of Brazilian territory still lack access to the conventional electrical grid especially in the Legal Amazon, where low population density, logistical challenges, and environmental restrictions make grid expansion unfeasible. In this context, the Mais Luz para a Amazônia (MLA) program has played a strategic role by implementing SIGFIs, which operate autonomously and ensure a basic electricity supply for families living in remote regions.

However, operating these systems presents significant technical and operational challenges. The intermittency of solar radiation requires the use of battery storage systems to guarantee continuous power supply during nighttime and consecutive days of low sunlight. Furthermore, factors such as long distances to maintenance centers, logistical transportation difficulties, environmental constraints, and the climatic variability of the Amazon make SIGFI management and maintenance complex and costly tasks.


10.18086/swc.2025.07.09 Available at http://proceedings.ises.org

Recent studies (Sens Neto et al., 2024) show that the reliability of SIGFIs depends not only on the technical conditions of the system but also on user behavior, which directly affects energy balance and component lifespan. Improper load usage and a lack of understanding of system limits can lead to overloading, recurrent failures, and premature battery degradation.

In this context, this study analyzes the performance of three Individual Photovoltaic Generation Systems with Intermittent Sources (SIGFIs) installed in the Legal Amazon, in the locality of Sena Madureira (AC), each with a nominal capacity of 80 kWh/month. Monitoring was conducted over 31 days in January 2025 to evaluate the operational behavior of users with different consumption profiles.

## 1.1 Context

The region where the systems were installed is located in the state of Acre, specifically in the Sena Madureira macroregion, characterized by a humid tropical climate and high annual rainfall, factors that directly influence the efficiency of autonomous photovoltaic systems. The average solar irradiation ranges from 3.8 to 4.2 kWh/m²·day, with a significant reduction during the rainy season. These conditions require greater battery bank autonomy and proper energy management to ensure continuous operation. Access to the region is limited, with fluvial routes and roads of difficult trafficability, which makes technical maintenance more challenging. Due to these characteristics, the area represents a suitable environment for evaluating the performance of SIGFIs under real operating conditions, considering both climatic aspects and the specific usage patterns of the communities served (INMET, 2025). Table 1 below presents the characteristics of the region where the SIGFIs were installed, and Fig. 1 shows the location of the microregion on the map of the state of Acre.

**Table 1 – Characteristics of the Sena Madureira region (Adapted from Labren, 2023).**

| Characteristic | Sena Madureira |
|---|---|
| Average annual temperature | ~ 24,8 °C |
| Average annual rainfall | ~ 2.017 mm |
| Average monthly global irradiation | 3,8 – 4,2 kWh/m²·day |
| Average annual daily sunshine | 4 h |

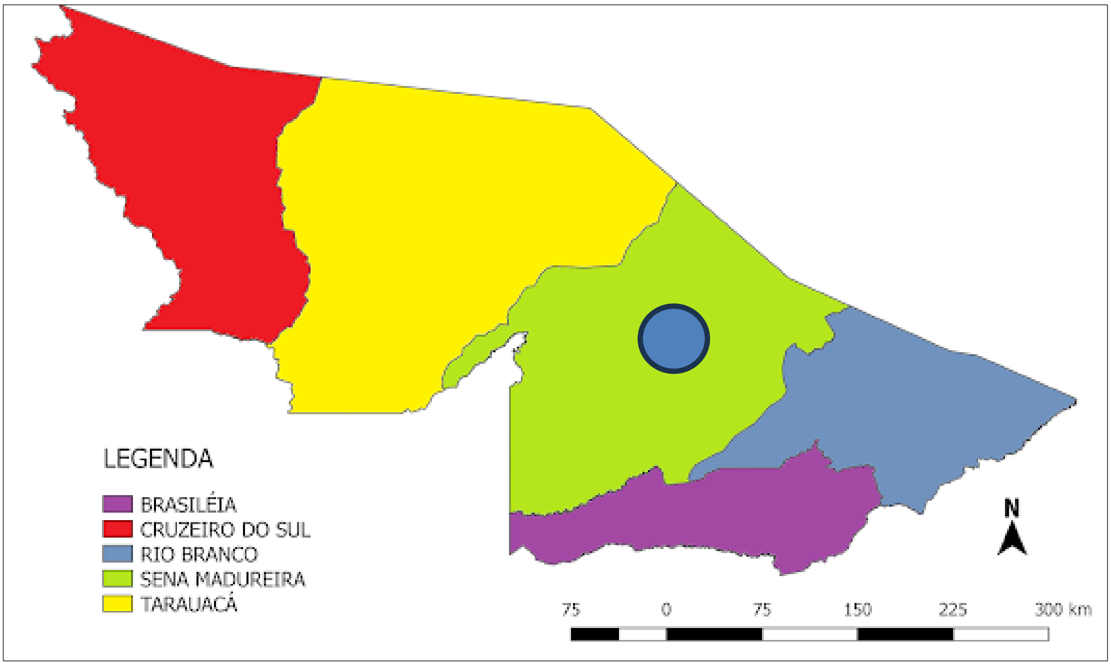


**Fig. 1 – Microregions of Acre** (Adapted from Infoescola, 2023).

## 2. Methodology

The three analyzed SIGFIs have a standard SIGFI-80 configuration, with a nominal voltage of 48 VDC, 36 hours of autonomy, a maximum load of 1,250 W, and a designed consumption of 2,650 Wh/day. With this configuration, the system can operate continuously and stably, provided that the connected loads remain within the limits defined in the design. However, when additional equipment is connected or unplanned increases in consumption occur, the system may become overloaded, reducing autonomy and compromising storage performance. Under these conditions, the SIGFI's protection mechanisms are automatically triggered, shutting down the system to prevent damage to the battery bank and other electronic components.

System operation is restored only after the minimum state of charge level of the battery bank has been recovered, ensuring reliable operation and system integrity. This protection strategy is essential to extend equipment lifespan and preserve the energy performance of the SIGFI, especially in remote regions of the Amazon, where access to corrective maintenance is limited.

The description of the SIGFI-80 configuration is presented below in Table 2:

**Table 2 – System description.**

| Characteristic | SIGFI-80 |
|---|---|
| Consumption | 2650 (Wh/day) |
| Maximum demand | 1250 (W) |
| DC system voltage | 48 (V) |
| Minimum usable battery capacity (with losses) | 138 Ah (6.625 Wh) |
| Minimum usable battery capacity (without losses) | 110 Ah (5.300 Wh) |

## 2.1 SIGFI and Its Components

The three SIGFIs have a standard configuration of SIGFI 80 kWh/month, and according to Sens Neto et al. (2024), the equipment that composes the SIGFI-80 includes photovoltaic modules, a charge controller, an inverter, and a lithium-ion battery bank, which operate in an integrated manner to ensure the continuous supply of electrical energy in isolated systems. The following section presents a detailed description and functional analysis of each component that constitutes the analyzed SIGFI configuration.

**Lithium-ion Battery – INTELBRAS 24V 100Ah 24S100**

Lithium-ion batteries constitute the main storage element of the SIGFI. They stand out for their high energy density and large number of charge and discharge cycles, ensuring a longer lifespan compared to lead-acid batteries. In addition, they are integrated with a Battery Management System (BMS), which monitors and controls operating parameters, ensuring efficient and safe performance. Thanks to technological advances and cost reductions, this type of battery has proven to be one of the most suitable alternatives for small-scale isolated system applications.

**Charge Controller – INTELBRAS ECM 6048**

The charge controller is responsible for managing the flow of energy between the photovoltaic modules, the battery bank, and the inverter, ensuring efficient charging and preventing overcharging or deep discharging. This component is essential for maintaining voltage within safe ranges, preserving battery durability and system stability. Its function is to balance the energy generated and the energy stored, compensating for daily variations in solar generation and electrical demand.

**Inverter – INTELBRAS ISV 1501**

The inverter converts direct current (DC) energy from the batteries or photovoltaic modules into alternating current (AC) energy, which is used by household appliances. In addition to performing the conversion, it serves as a control point between the generation system and the end loads, monitoring the stability and efficiency of the delivered energy. Modern inverters, equipped with MPPT (Maximum Power Point Tracking) technology, optimize energy extraction from the solar modules, ensuring better utilization of photovoltaic generation.

**Photovoltaic Module – INTELBRAS EMSH 555**

The photovoltaic module is the component responsible for the direct conversion of solar radiation into electricity through the photovoltaic effect. In a SIGFI system, the modules are combined to meet the projected daily energy demand, forming the generation subsystem that supplies the charge controller and subsequently the battery bank and inverter. The overall efficiency of the system depends on both the quality of the modules and the local environmental conditions, such as temperature, shading, and solar irradiation levels.

Fig. 2 bellow presents the schematic of the single-line diagram of the SIGFI-80 kWh/month system.

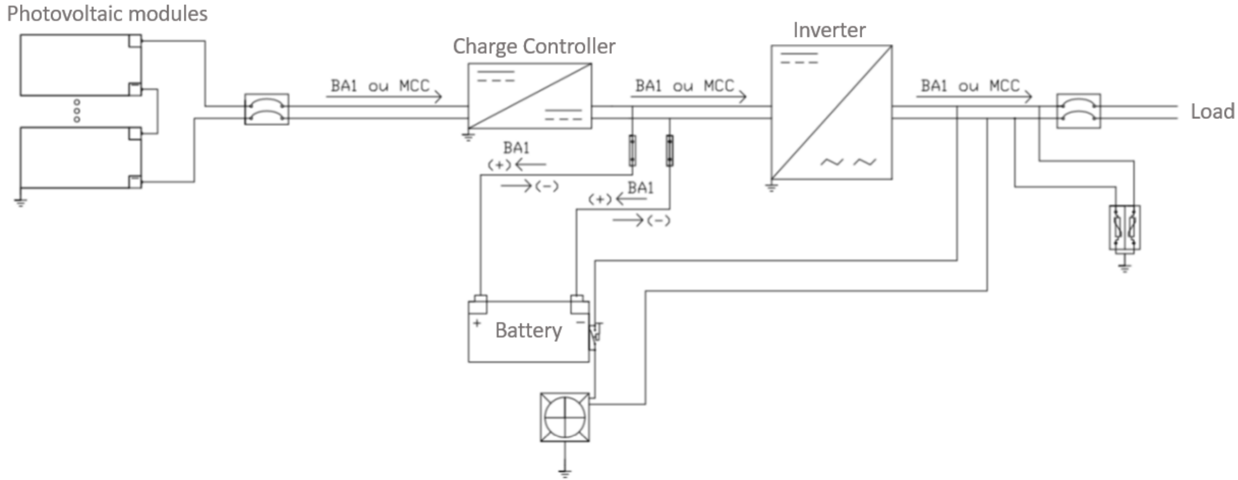


**Fig. 2 – Single-line diagram of the SIGFI 80 kWh/month system.**

In Fig. 2, the power flow represented by the acronym MCC (Module–Controller–Load) indicates the flow between the photovoltaic module, charge controller, and load. This subsystem represents the energy generated by the modules, which always flows toward supplying the load. In this case, the power supply occurs directly to the load, without considering the battery. It is assumed here that the batteries are fully charged.

For the BA1 (Li Battery) power flow, this subsystem represents the energy stored or consumed by the batteries; this flow can occur in two directions. When the flow is toward the batteries (charging), the sign is considered positive. When the flow is toward the load (discharging), the sign is considered negative.

## 2.2 Method of Analysis

Field analyses of the SIGFIs were conducted over a 31-day operating period corresponding to January 2025, with data obtained directly from the charge controller. The information was collected and stored during preventive and corrective maintenance visits, which were carried out whenever users reported system occurrences. Additionally, to that, data from the following months were analyzed in order to verified the impact of detailed technical guidance provided by the maintenance team in February 2025.

During these visits, operational data were extracted and analyzed to identify the causes of failures or interruptions in operation that could be associated with technical equipment issues, adverse environmental conditions, or even improper system use, such as overload situations (Sens Neto et al., 2024).

# 3. Results

Corrective maintenance records were obtained from incidents reported directly by the users, who contacted the responsible field service teams for on-site assistance. During these visits, operational data were extracted from the charge controller, enabling a detailed analysis of the system's behavior before and during failures. This methodology allowed for precise identification of the causes of interruptions, distinguishing failures resulting from technical equipment issues from those caused by improper use or system overload.

During the monitoring period, it was observed that the three systems exhibited distinct energy consumption behaviors:

- SIGFI A: Showed consumption above the projected level, resulting in automatic shutdowns and the need for corrective maintenance.
- SIGFI B: Maintained consumption within the nominal range, operating in a stable and continuous manner.
- SIGFI C: Recorded consumption below the estimated level, with no failures or interruptions observed.

As shown in the figures below, the graphs demonstrate that the three analyzed systems exhibited distinct consumption patterns and operational responses throughout the monitoring period. This difference in performance reflects both the specific usage profile of each household and the degree of alignment between the energy demand and the nominal capacity of each SIGFI.

The data for SIGFI A, shown in Fig. 3 below, were obtained during a corrective maintenance intervention prompted by reports of automatic shutdowns and instability in the energy supply. The collected information revealed consumption patterns exceeding the nominal design limits, particularly during peak hours between 9:00 – 11:00 a.m. and 6:00 – 8:00 p.m. The analyses indicated that the system repeatedly operated near its safety limit, resulting in deeper discharge cycles and temporary reductions in the battery bank's efficiency.

Although the system includes built-in protection mechanisms, occasional interruptions were recorded due to momentary overloads. Following the technical guidance and continued monitoring in the subsequent months, a gradual improvement in consumption behavior was observed, with a reduction in occurrences and the restoration of operational stability which will be presented in the following sections.

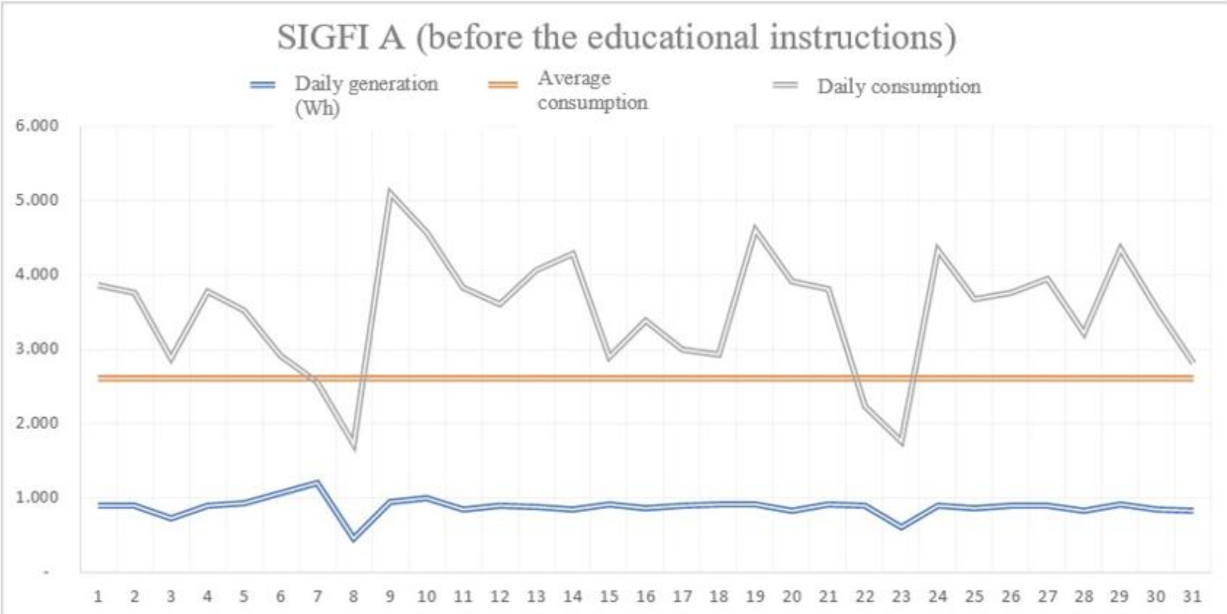


**Fig. 3 – SIGFI A energy consumption exceeding the permitted level during January 2025**

For SIGFI B, the information was collected during preventive maintenance, using the data provided by the charge controller. At the time of data collection, no consumption records were identified that exceeded the energy limit established in the system's design. As illustrated in Fig. 4, the equipment operated within the expected nominal range, with no overload alerts or failures related to the performance of the controller or the batteries.

Minor variations in power were observed throughout the month, represented by transient consumption peaks, all of which remained within the operational safety margin. On some days, the controller recorded peaks up to 38% above the average operating level; however, these were not sustained long enough to trigger the protection system or compromise overall functionality.

Thus, SIGFI B demonstrated stable performance, with good response from both the photovoltaic array and the battery bank, indicating a balance between household demand and installed capacity. Nevertheless, if these consumption peaks were to occur frequently, they could eventually compromise the lifespan of the components involved in the SIGFI's operation.

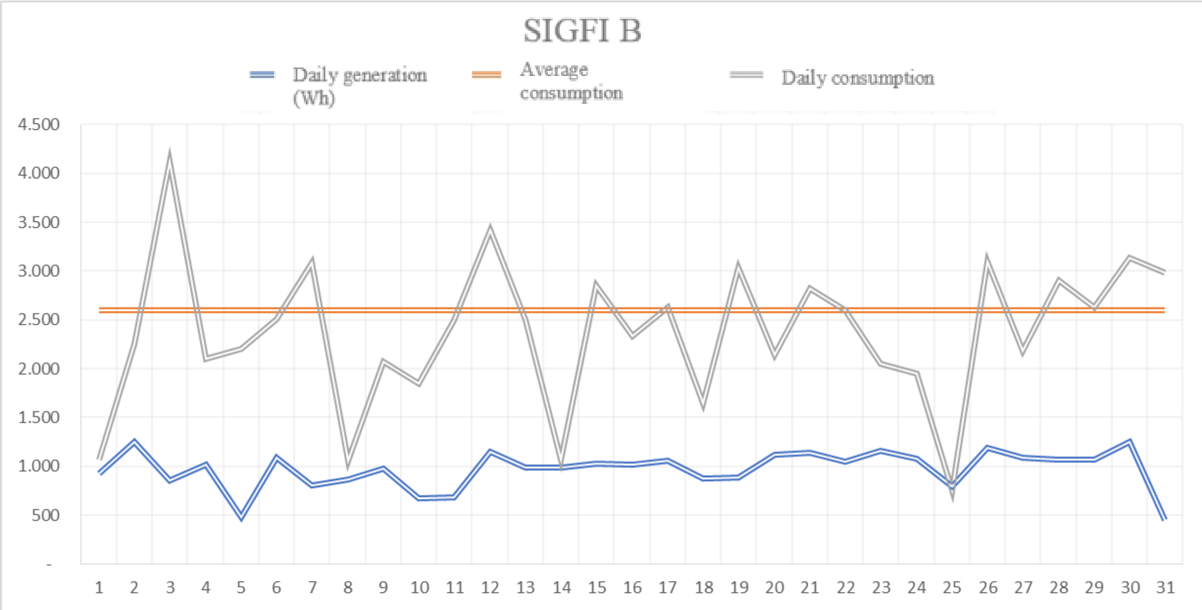


**Fig. 4 – SIGFI B energy consumption remaining within the designed operating limits during January 2025.**

For SIGFI C, shown in Fig. 5, the information was also obtained during preventive maintenance through direct extraction of operational data from the charge controller. At the time of analysis, the system showed no signs of overload or operation outside the parameters defined in the design.

As illustrated in the graph, the operational behavior remained consistent throughout the observation period, with no significant energy peaks unlike what was observed in SIGFI A and B. The household supplied by this system had an energy demand lower than the nominal capacity of the SIGFI, which resulted in an increased safety margin and the absence of operational failures.

This condition contributed to maintaining electrical stability and eliminated the need for corrective interventions, demonstrating an appropriate system design and a consumption profile compatible with the available generation.

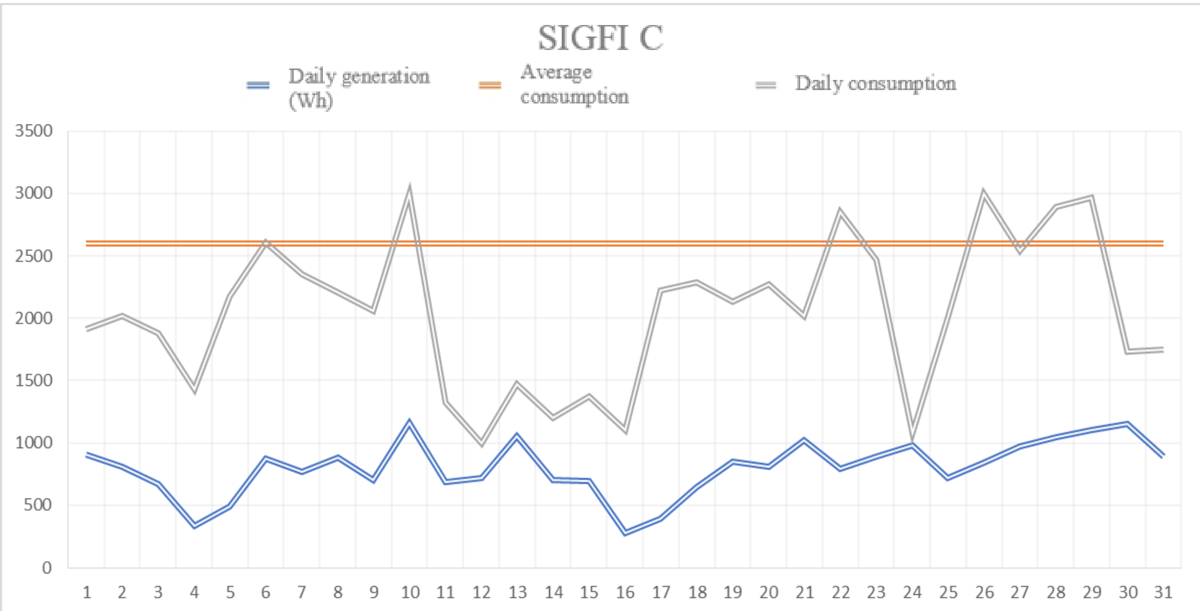


**Fig. 5 – SIGFI C energy consumption below the designed operating limits during January 2025.**

Considering the performance of SIGFI A, a targeted monitoring plan was implemented for this consumer unit. In February 2025, the user received technical instructions on the proper use of the system, including guidance on load prioritization, consumption limits, and daily usage control. After three months of continuous monitoring, with monthly data extraction from the charge controller, a significant reduction in overload occurrences and operational failures was observed, along with an improvement in usage behavior and greater system stability.

Fig. 6 below presents the energy consumption of SIGFI A throughout March 2025.

These results reinforce that user guidance and awareness actions play a fundamental role in the efficiency, reliability, and durability of autonomous photovoltaic systems installed in isolated areas.

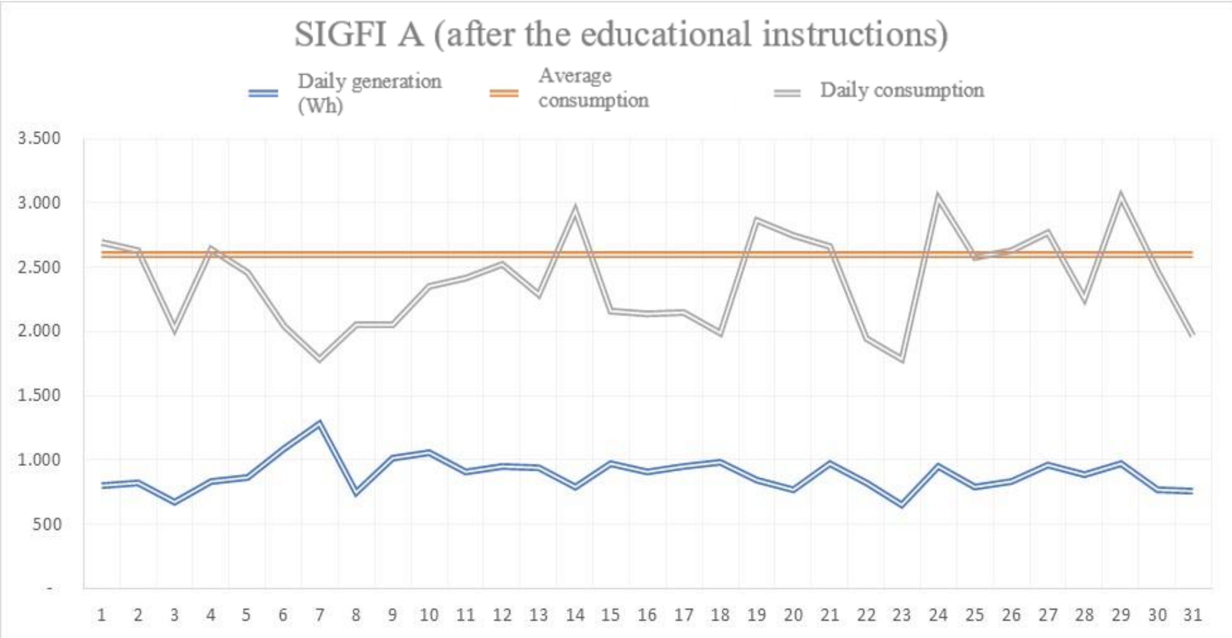


**Fig. 6 – Improvement in SIGFI A energy consumption in March 2025.**

In the monitoring of SIGFI A, as shown in Fig. 6 above, it is possible to observe that the system exhibited unstable energy consumption behavior throughout the monitored period particularly during the first days of recording, when sharp power peaks and abrupt variations in battery discharge levels were observed. This fluctuation reflects the non-linear use of the loads connected to the system, associated with moments of simultaneous operation of high-power equipment.

A detailed analysis of the data indicates that, although the charge controller operated properly in protecting the system, the occasional demand above the nominal capacity triggered recurrent safety mechanisms and temporary automatic shutdowns.

In the April 2025 records (Fig. 7 below), a trend toward stabilization in the consumption profile can be noted. The graphs show a reduction in current peaks and better balance in the depth of discharge of the battery bank. This change is associated with the adoption of more conscious usage practices, such as distributing loads throughout the day and turning off nonessential equipment during periods of low solar irradiation. In addition, the frequency of overload events decreased noticeably, indicating greater compatibility between the consumption pattern and the system's design capacity.

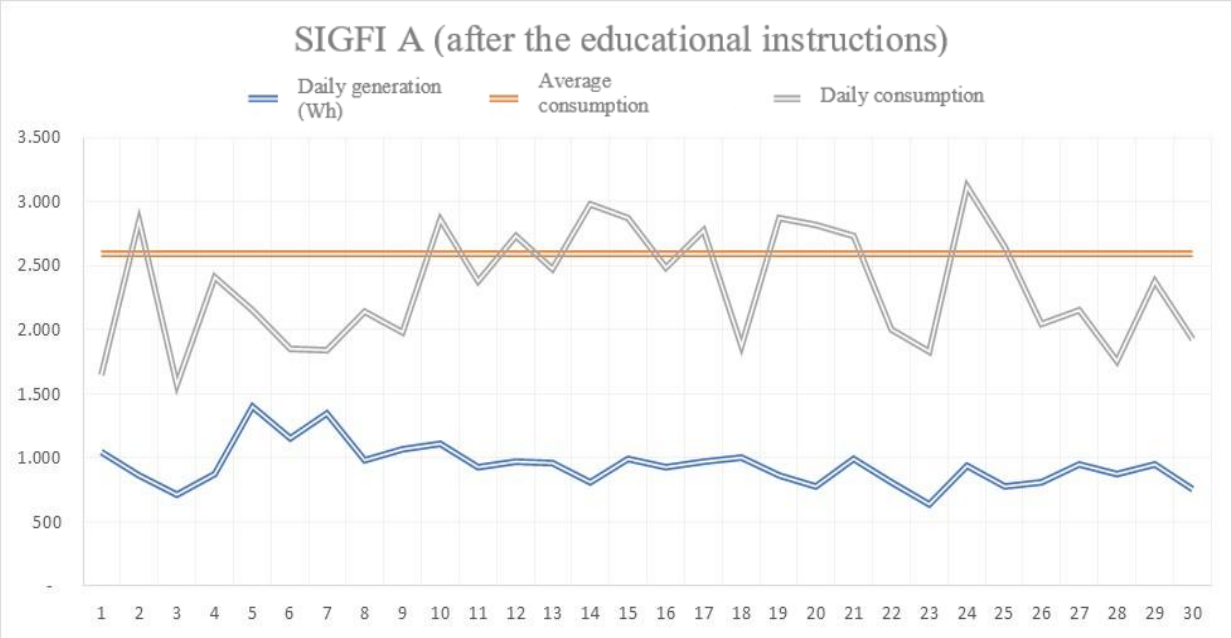


**Fig. 7 – Improvement in SIGFI A energy consumption in April 2025.**

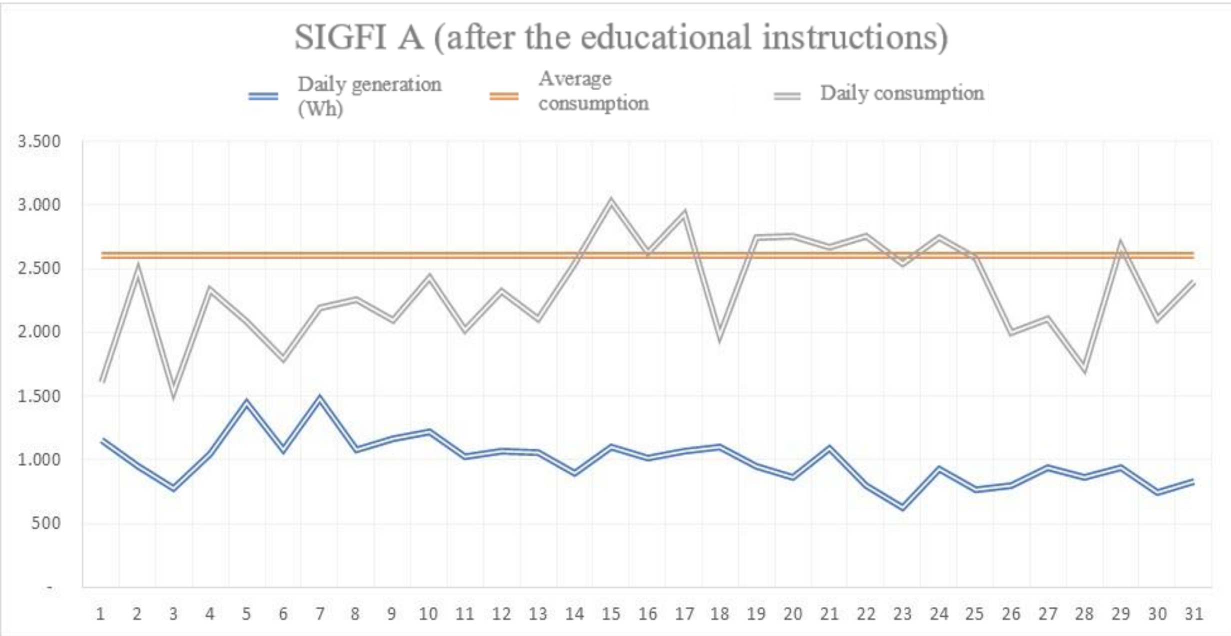


**Fig. 8 – Improvement in SIGFI A energy consumption in May 2025.**

In May 2025, as shown in Fig. 8 above, the system demonstrated consolidated and stable operational behavior, with power variations remaining within expected limits and the battery state of charge maintained at appropriate levels. It is evident that the technical guidance interventions had a positive effect, resulting in increased system availability and a lower incidence of failures. The monthly monitoring data indicate that, over the course of the quarter, there was continuous improvement in energy efficiency, reinforcing the effectiveness of the user training and monitoring process.

Overall, the results obtained demonstrate that operational and behavioral factors exert a direct influence on the performance of autonomous photovoltaic systems. The experience with SIGFI A highlights the importance of continuous monitoring, user training, and preventive maintenance all of which together ensure greater reliability, sustainable performance, and extended equipment lifespan.

The comparative analysis among the three evaluated systems confirms that the adoption of good usage practices is just as important as proper technical sizing, making it an essential element for the success of rural electrification programs based on decentralized photovoltaic generation.

## 4. Discussion and conclusions

The comparative analysis of the three SIGFI systems revealed significant differences in operational behavior and in the interaction between the user and the system. The technical monitoring carried out allowed for a deeper understanding of how usage factors, consumption habits, and daily practices directly influence energy performance, operational stability, and equipment lifespan.

**SIGFI A** initially presented a consumption pattern above its design capacity, resulting in temporary overloads, recurrent activation of protection mechanisms, and reduced efficiency of the battery bank. This behavior was mainly attributed to the simultaneous use of high-power equipment and the lack of proper daily energy management practices by the user.

After the implementation of specific technical guidance in February 2025, a significant change in usage patterns was observed, with a reduction in demand peaks, as shown in the previous graphs. This change resulted in the elimination of automatic shutdowns, which had occurred biweekly before the instructions, with no new events recorded during the analysis period between March and April 2025. Consequently, a notable improvement in the system's operational stability and greater regularity in the supply of energy to essential loads were verified.

These results demonstrate that user training and educational actions, combined with continuous technical monitoring, are decisive factors for the efficient and reliable performance of isolated photovoltaic systems, especially in regions where users have limited technical knowledge.

**SIGFI B** maintained operation within its nominal range throughout the observation period, showing a good balance between installed capacity and daily consumption. The recorded variations were occasional and short-lived, not affecting system autonomy or triggering protection devices. Meanwhile, **SIGFI C**, which supplied a household with an energy demand below the projected value, displayed complete operational stability, with no failures or need for corrective maintenance. This outcome reinforces the importance of system sizing that aligns with the real consumption profile, contributing to longer system lifespan and reduced maintenance costs.

Overall, the results indicate that SIGFI performance depends not only on technical characteristics but also on user behavior and energy consumption management. The case of **SIGFI A** showed that simple interventions involving user guidance and technical monitoring can reduce failures and improve system efficiency in the short term, producing a positive impact on both supply reliability and operational sustainability.

Finally, it is concluded that integrated actions involving monitoring, user training, and preventive maintenance should be systematically incorporated into rural electrification programs based on autonomous photovoltaic systems. These practices enhance investment returns, ensure continuous and safe operation, and promote the rational use of energy in isolated communities, strengthening the role of SIGFI as a viable and sustainable solution for expanding access to electricity in the Brazilian Legal Amazon.

## 5. Acknowledgments

The authors express their gratitude to their colleagues from the Laboratório Fotovoltaica – UFSC for their valuable discussions and contributions related to the topic addressed in this article. They also thank the partner companies for providing information and for their participation in meetings that enriched and made this research possible. This research was carried out within the scope of the activities of the National Institute for Technological Development of Photovoltaic Solar Energy Applications, INCT-DAESF, CNPq/MCTI/Brazil, Process 408486/2024-4.

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