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ORIGINAL ARTICLE

Rational use of energy and photovoltaic generation: sustainable strategies for northern Brazil

Uso racional de energia e geração fotovoltaica: estratégias sustentáveis para o norte do Brasil

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Abstract: Concern about energy efficiency and renewable energy has emerged during the global energy crisis. This issue is particularly relevant in Roraima, a state in northern Brazil, due to its dependence on isolated electrical systems. Boa Vista, the capital, has high average annual temperatures and the country's highest average residential electricity consumption, which creates an opportunity for sustainable solutions. Given the abundant availability of solar radiation in the region, photovoltaic energy has emerged as a promising alternative for meeting energy demands sustainably and economically. In this work, case studies in three homes and on a university campus in Boa Vista made it possible to analyze the energy infrastructure and challenges and propose solutions to increase energy efficiency in the state and the region. The novelty of this work lies in integrating academic perceptions about energy efficiency and photovoltaics with practical initiatives implemented on campus. The study contributes to the theoretical-scientific discourse by exploring innovative strategies to increase energy efficiency and the use of photovoltaics, helping to advance the state of the art in this field. The managerial-applied contribution guides authorities in formulating policies for technological development and the rational use of energy.

Keywords: Energy efficiency; Distributed photovoltaic generation; Photovoltaic energy; Sustainable energy supply.

Resumo: A preocupação com a eficiência energética e a energia renovável ganhou destaque durante a crise energética global. Isso é particularmente relevante em Roraima, um estado no norte do Brasil, devido à sua dependência de sistemas elétricos isolados. Boa Vista, a capital, tem altas temperaturas médias anuais e o maior consumo médio de eletricidade residencial do país, o que cria uma oportunidade para soluções sustentáveis. Dada a abundante disponibilidade de radiação solar na região, a energia fotovoltaica surgiu como uma alternativa promissora para atender às demandas de energia de forma sustentável e econômica. Neste trabalho, estudos de caso realizados em três residências e em um campus universitário de Boa Vista permitiram analisar a

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infraestrutura e os desafios energéticos e propor soluções para aumentar a eficiência energética no estado e na região. A novidade deste trabalho está na integração das percepções acadêmicas sobre eficiência energética e energia fotovoltaica com iniciativas práticas implementadas no campus. O estudo contribui para o discurso teórico-científico ao explorar estratégias inovadoras para aumentar a eficiência energética e o uso de energia fotovoltaica, ajudando a avançar o estado da arte nesse campo. A contribuição gerencial aplicada fornece orientação às autoridades na formulação de políticas para o desenvolvimento tecnológico e o uso racional de energia.

Palavras-chave: Eficiência energética; Geração fotovoltaica distribuída; Energia fotovoltaica; Fornecimento de energia sustentável.

1 Introduction

Contemporary society is increasingly aware of the need to adopt practices that promote rational and sustainable electricity usage. This imperative arises from the urgency of mitigating the impacts of the greenhouse effect and preserving the planet's natural resources (Sun et al., 2019). The rational use of energy has two crucial dimensions: reducing costs and minimizing environmental damage. These dimensions involve a holistic approach encompassing energy conservation, efficiency, and effective management. Energy conservation is linked to consumption habits and patterns and the use and consumption framework, including ownership, operation, and equipment maintenance. Efficiency refers to the relationship between the output and input of energy in a system or piece of equipment. Generally, improving this efficiency involves replacing or modifying equipment and processes to achieve the same result with lower energy consumption. In fact, among the various factors that can increase electricity costs are the use of obsolete machinery and high tariffs at certain times (Menezes et al., 2024). Finally, energy management goes beyond behavioral, organizational, and technological approaches in promoting the rational use of energy since its administration demands continuous conservation and efficiency efforts (Filippo, 2018). These measures together improve energy performance and contribute to increasing energy efficiency (EE), which implies reducing energy consumption to achieve the desired result (Martins et al., 2022).

In many developing nations, the high electricity consumption and cost in private buildings and public institutions are urgent concerns (Opoku et al., 2020). Despite this, Brazil still invests less in EE than other countries (ACEEE, 2022). However, the country has great potential to improve EE during its continued economic growth through policies targeting the residential, industrial, and transportation sectors (Brasil, 2018a; EPE, 2024). The state of Roraima, located in the far north of Brazil, operates an isolated electricity system, being the only state not integrated into the National Interconnected System (SIN), a sizeable hydrothermal system for producing and transmitting electricity in the country. Currently, the generation in the SIN goes beyond hydrothermal systems and includes wind and solar power. As a result, Roraima faces significant energy supply challenges, justifying the importance of studying this issue. In this state, energy consumption is highly concentrated in the residential sector (51.1%), followed by the commercial sector (22.2%), the public sector (10.8%), and the public service sector (3.0%), the rest being distributed among other sectors. In 2022, Roraima's residential sector's average monthly electricity consumption was 295 kWh, while the national average was 173 kWh/month. Despite the 2.4% reduction compared to the previous year, Roraima has the highest average residential consumption of any state in the country. By comparison, the state of São Paulo recorded an average residential consumption of 188 kWh/month in the same year (EPE, 2024).

In Boa Vista, homes, businesses, services, and public institutions depend on electricity mainly for lighting, operating industrial machinery and equipment, refrigeration and air conditioning systems, and other essential activities. Implementing strategies at all local community levels to promote efficient energy use and overcome regional supply challenges is necessary. One strategy is generating renewable energy through distributed photovoltaic micro- and mini-generation. The rational use of energy, combined with distributed photovoltaic generation (DPVG) and effective energy management, can mitigate supply problems and prevent disturbances in the electricity grid. In this context, the implementation of DPVG in Roraima is justified by its many benefits, including postponing investments in transmission and distribution network expansion, reducing technical losses, and diversifying the energy matrix. Moreover, DPVG leverages the region's abundant solar irradiation, which averages 4.9 kWh/m^2 per day (CRESESB, 2018).

The literature analysis on EE and DPVG revealed the research of some authors in this field of study. Opoku et al. (2020) conducted a case study on sustainable EE and solar energy measures to reduce electricity costs in public higher education institutions in Kumasi, Ghana. The results showed a significant electricity savings opportunity of 163,400 kWh/month, or approximately 5%, with renovations to the administrative buildings' air-conditioning units, lighting systems, and fans. Almushaikah & Almasri (2021) investigated various EE measures and the prospects for solar energy for the residential sector in central Saudi Arabia. The results indicated that applying thermal insulation to walls, roofs, and windows should be prioritized to promote energy conservation. These measures reduced energy consumption by approximately 27% for walls, 14% for roofs, and 6% for windows. Grande-Acosta & Islas-Samperio (2020) analyzed four solar energy options across the residential, commercial, and public sectors. Their findings indicate that, by 2030, the proposed mitigation measures could reduce greenhouse gas emissions by 23.5 million tons of carbon dioxide equivalent (MtCO2e) compared to the projected emissions trend. The reductions are distributed as follows: 19 MtCO2e in the residential sector, 2.6 MtCO2e in the commercial sector, and 1.9 MtCO2e in public services. Hafaifa et al. (2020) developed a mechanism to optimize the use of photovoltaic panels in power generation. Due to the non-linear nature of the panels' energy production, which varies according to light intensity and temperature, the proposed mechanism uses a fuzzy control of the photovoltaic system and an algorithm to search for the optimum power point, allowing maximum energy to be extracted from the panels. Li et al. (2021) proposed a method for evaluating the EE of photovoltaic systems using hierarchical analysis and fuzzy evaluation. It analyzes the factors that influence system efficiency and establishes an evaluation system with three categories: static index, dynamic index, and loss index. Hierarchical analysis determines the weight of each index, and fuzzy calculation defines the level of energy efficiency. Validation was carried out using a photovoltaic station in northwest China, showing that the method objectively reflects the actual efficiency of the system, serving as a reference for similar evaluations.

These studies provide a crucial contribution to the study. However, Popkova & Sergi (2021) highlight a research gap in developing energy EE management strategies, especially in developing countries. Al-Shahri et al. (2021) reinforce this need and stress the importance of further exploring solutions for the transition to renewable energy, such as photovoltaics (PV). They point out that there is still a gap in creating optimal designs for hybrid power generation systems, and more research is needed to validate models using different load profiles. Therefore, the research question that motivated this work is: How can Roraima's energy performance, particularly in Boa Vista, be improved to optimize energy consumption, achieve cost savings, and promote sustainable alternatives in the far north of Brazil? This study addresses the research question by proposing solutions to improve energy efficiency in Roraima based on case studies conducted in private homes and on a university campus in Boa Vista.

Following this introduction, Section 2 briefly overviews the theories on EE and DPVG and examines energy consumption in Roraima. Section 3 outlines the research method. Section 4 presents and discusses the case studies. Section 5 details the proposed solutions. Section 6 concludes the work, addressing the contributions, implications, and indications for future research. Finally, the references are listed at the end of the manuscript.

2 Theoretical framework

2.1 Energy efficiency and photovoltaic power generation

The quest for EE and DPVG is an environmental imperative and a catalyst for technological innovation and sustainable development. Countries that excel in this endeavor mitigate the adverse impacts of climate change and position themselves as leaders in the research and implementation of advanced energy solutions. Hartwig et al. (2017) consider EE one of the fastest and most cost-effective contributions to a sustainable, secure, and affordable energy system. They cite that the so-called non-energy benefits, co-benefits, or multiple benefits of EE are receiving increasing interest from policymakers and the scientific community. In response to concerns about pollution and global warming from electricity generation, photovoltaic sources have emerged as a leading alternative for producing clean energy (Ayub et al., 2014). The adoption of EE and DPVG aligns with the new world energy order philosophy. The Brazilian government aims to save 10% in final electricity consumption by 2030 through the National Energy Plan (Brasil, 2007). Addressing this challenge requires promoting the transition to cleaner and more sustainable energy sources, including solar, wind, and hydroelectric power. Incentives for research, development, and implementation of low-carbon technologies and effective climate policies are essential to reduce the carbon footprint associated with electricity generation globally. In this sense, ANEEL's Energy Efficiency Plan (EEP), launched in 1998, plays a crucial role since it aims to promote the efficient use of electricity, reduce waste, and involve various projects to optimize energy consumption in different sectors (Brasil, 2024b).

2.2 Characterization of energy consumption in the state of Roraima

The state of Roraima has peculiar characteristics regarding electricity distribution concessions, especially as it is the only concession electrically isolated from the SIN. Between 2001 and 2019, Roraima's primary energy source was Venezuela's Simón Bolívar hydroelectric plant, also known as Guri. With a capacity of 10,200 MW, it is one of the largest hydroelectric plants in the world (Brasil, 2018a). The considerable distance from the generating source and a drought that reduced Venezuela's generating capacity by 70% and led to energy rationing were crucial factors contributing to the precarious energy supply in Roraima. Two 60 MW thermoelectric plants were installed in Boa Vista in 2010 to reduce dependence on energy imports from Venezuela and avoid rationing.

In the latter half of 2013, the Brazil-Venezuela interconnection began experiencing more severe issues. Analysis revealed that the interconnector could only import 95 MW at the time. Increasing the thermoelectric generation to meet the excess demand was necessary, adding 129.1 MW to the existing 60 MW, resulting in 189.1 MW by 2015. Concurrently, the National Electric Energy Agency (ANEEL) authorized the early installation of a 35 MW static compensator at Eletronorte's 230 kV substation (now SE Boa Vista), initially intended for SIN interconnection. This initiative allowed for an additional 35 MW in the exchange with Venezuela, bringing the total to 130 MW. However, in March 2019, the energy transmission from Venezuela was abruptly halted due to political decisions. As an alternative, Roraima has since relied heavily on fuel-fired thermoelectric plants, an expensive and polluting source consuming between 700 and 1.1 billion liters of fuel daily (EDRR, 2019).

Roraima has historically relied on thermal generation. Until 2018, energy distribution was managed by Eletrobras Distribuição Roraima (EDRR). The concession then passed to Boa Vista Energia SA (BOVESA) and subsequently to the Oliveira Energia group with experience in Manaus. Currently, Roraima Energia holds the concession (Roraima Energia, 2023). Given the region's average daily global irradiation of 17.83 MJ/m^2/day, implementing measures to enhance EE alongside DPVG systems is a viable solution to mitigate electricity shortages in Roraima. This approach would boost the adoption of solar energy, diversify the energy matrix, and promote renewable sources. Meanwhile, the government must regulate and plan the energy system to ensure viability and supply security with minimal social costs (Resende et al., 2018).

3 Research method

This study takes an empirical-normative approach, using observable data collection to analyze the energy infrastructure and efficiency challenges in buildings in Boa Vista, called units of consumption (UC). The aim is to understand their relationships and propose solutions, establish a benchmark for Roraima and the region, and legitimize specific issues and processes related to energy consumption. The study was based on case studies carried out in three private residences (UC1, UC2, and UC3) and at the Boa Vista University Center (CBV) (UC4) from 2014 to 2018. The seven steps involved in developing the work are illustrated in the flowchart in Figure 1 and presented in detail in the following subsections.

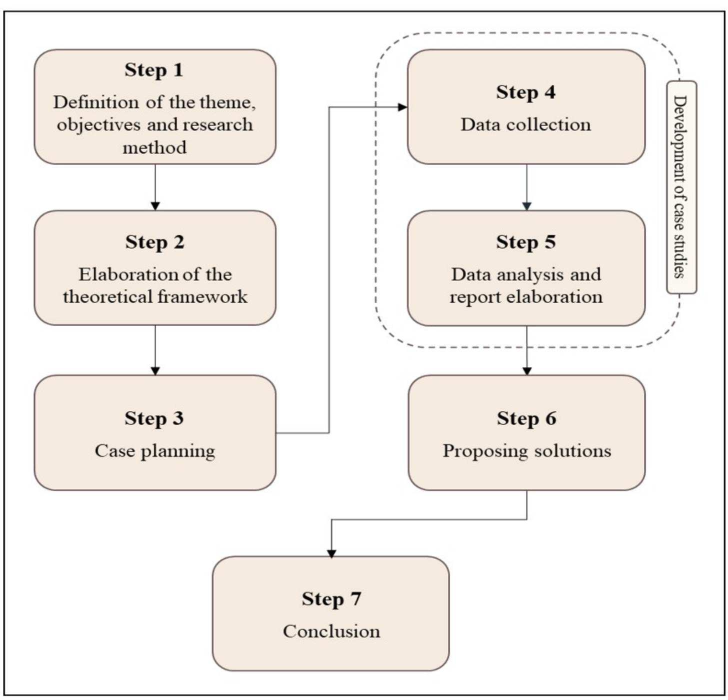

Figure 1. Flowchart of the study. Source: The authors.

3.1 Step 1 – Definition of the theme, objectives, and research method

At this stage, the key elements of the work were established, including the definition of the topic, the research gap, the objectives, and the research method. The topic's potential was recognized given the opportunity to adopt the binomial "energy efficiency and renewable distributed generation" - a global trend to combat the effects of climate change - in a Brazilian federal unit with exceptionally high energy consumption and isolated energy infrastructure.

3.2 Step 2 – Elaboration of the theoretical framework

The research was based on analyzing the most relevant articles and reviews on EE and DPVG. Although the case study covers the period from 2014 to 2018, the literature search covered the period from 2019 to 2023 to obtain the state of the art on the subject. Initially, the search was carried out using the term "energy efficiency" in the title on the Scopus platform, resulting in 6,702 documents. A second search was then conducted using the term "distributed photovoltaic generation," which yielded 29 papers. Analysis of these 29 documents, together with the 30 most cited in the first search, provided insights that guided the findings and analysis of the case studies. Finally, the keywords "energy efficiency" and "distributed photovoltaic generation" and their respective variations were combined to establish the relationship between these two terms, which resulted in 27 additional documents. In addition, searches on government websites and official regulatory agencies assisted in characterizing energy consumption in Roraima.

3.3 Step 3 – Case planning

Energy demand in residential units mainly concentrates on electricity needs for lighting, air conditioning, fridges, freezers, and household appliances. In the case of the campus, there is also a demand for electricity for the external lighting of its facilities, such as the courtyard, sports courts, and parking lot. Table 1 describes the objects of study used in this research.

Table 1. Buildings used as objects of study.

Object	Description	Location reference
UC1	Residence built on a 600 m^2 plot, located in the Pricumã neighborhood of Boa Vista, in Bioclimatic Zone 8 (BZ 8), at geographical coordinates 2°48'37" N and 60°41'51" W, with an elevation of 81.9 m. The built area is 142 m^2 and contains 1 balcony, 1 living room, 3 bedrooms, 1 en-suite, 1 kitchen, 1 laundry area, and 1 bathroom and is inhabited by two residents.	Google (2018a)
UC2	Residence built on a 600 m^2 plot, located in the Caçari neighborhood, Boa Vista, in BZ 8, at geographical coordinates 2°51'43" N and 60°40'14" W and elevation 76.9 m. The built area is 360 m^2 and contains 1 veranda, 1 living room, 3 bedrooms, 1 kitchen, 1 laundry area, 1 shared bathroom and 2 suites, and a swimming pool, and is inhabited by three residents.	Google (2018b)
UC3	Residence built on a 480 m^2 plot, located in the Paraviana neighborhood, Boa Vista, in BZ 8, at geographical coordinates 2°51'46" N and 60°39'53" W and elevation 70.3 m. The built area is 120 m^2 and contains 1 balcony, 1 living room, 2 bedrooms, 1 kitchen, 1 laundry area, and 2 communal bathrooms and is inhabited by six residents.	Google (2018c)
UC4	The CBV is in the Pricumã district of Boa Vista and occupies a total area of 69,760.55 m^2. It has more than a dozen buildings, totaling 27,500 m^2 of constructed area. The electrical infrastructure comprises a single meter at the supply point and a substation equipped with two 500 kVA transformers, reaching a total transformation capacity of 1,000 kVA.	Google (2018d)

UC = Unit of Consumption; BZ = Bioclimatic Zone.

In November 2017, the first DPVG was installed in a public sector building in Roraima at the CBV, with funding from ANEEL through EE programs. The DPVG has an installed capacity of 66 kWp and is located at the geographical coordinates 2°48'49" N and 60°41'38" W, identified by the code GD.RR.000.023.271. This facility was considered for analysis in this study. During the six months following its implementation, data was collected through low-voltage electrical measurements (127/220V) at the photovoltaic power generation point.

3.4 Step 4 – Data collection

Initially, the researchers contacted the companies and individuals involved, including the Federal Institute of Education, Science and Technology of Roraima (IFRR), Eletrobras Distribuição Roraima (EDRR), and the owners of the three residences in Boa Vista. UCs' and CBV's energy bills provided energy consumption records. Fronius Solar, a Canadian solar energy management company, provided the data on photovoltaic energy production and consumption in the CBV. The company's website shows the balance of energy generated and consumed in real-time and daily data archives (Fronius Solar, 2018). Measurements taken at the CBV supply point provided the EDRR data. The researchers collected data through continuous measurement at the campus delivery point over a typical period and by surveying internal and external lighting and air conditioning loads. Additionally, they gathered data on energy production at the DPVG source located at the CBV and on the historical temperature record of Roraima and its capital, Boa Vista.

Data collection involved the following items: (a) average monthly temperatures in the city of Boa Vista over 48 months; (b) electricity consumption data over twelve months in UC1, UC2, and UC3; (c) electricity consumption data over 48 months at UC4, and (d) six months of photovoltaic energy production and consumption data at the UC4.

3.5 Step 5 – Data analysis and report elaboration

Data processing prioritized only those essential to the research objectives. Data analysis for each case followed the four phases described below.

Phase 1: Develop a detailed description of each specific case, considering multiple sources of evidence.

Phase 2: Summary of the data obtained in each survey, including only the essential information and closely linked to the research objectives.

Phase 3: Construction of a demonstration panel for each case, providing a comprehensive and detailed view of the data and facilitating the drawing of valid conclusions related to the research.

Phase 4: Assessing the technical and economic feasibility of the CBV's DPVG source.

All the activities from the previous stages were summarized in a report to ensure the reliability and validity of the study. Table 2 summarizes the activities carried out.

Table 2. Panel showing the research data set.

Source of evidence	Activities carried out
Bibliographical research	Documentary analysis, gaps, state-of-the-art
Available resources	Characterization of the objects of study
EDRR data	Load surveys at three residences and the CBV
UC energy bills	Electrical measurements in Boa Vista residences
Energy supply point	Inspection and electrical measurements at the CBV
PV energy supply point	Electrical measurements on the DPVG source
Payback cash flow	Evaluation of the economic viability of the DPVG source

EDRR = Eletrobrás Distribuição Roraima; UC = Unit of Consumption; PV = Phovoltaic.

3.6 Step 6 – Proposing solutions

Considering the results obtained through data collection, specific actions were proposed to optimize the use of energy resources, implement more efficient technologies, and encourage sustainable practices in the region, including adopting photovoltaics. These measures aim to contribute to a more resilient and environmentally conscious future.

3.7 Step 7 – Conclusion

Finally, the conclusions emphasized the research question's answer and the established objectives' fulfillment. In addition, the authors highlight this work's theoretical-scientific and managerial-applied contributions and suggestions for future studies.

4 Presentation and discussion of the case studies

The case studies were conducted in Boa Vista, Roraima, the state capital, which historically records some of the highest average annual temperatures among Brazilian capitals (INMET, 2018). Its hot, tropical climate drives significant demand for refrigeration and air conditioning in residential and commercial settings. The temperature history enables us to establish a possible correlation between ambient temperature and energy consumption and demand in the city. The highest average monthly temperature recorded during the period studied was 31.94 °C, and the lowest was 28.10 °C. The highest maximum was 37.83 °C, and the lowest was 23.69 °C. It is worth noting that the range of temperature variations in the city over the 48 months is minimal and tends to be constant, as illustrated by the graph in Figure 2.

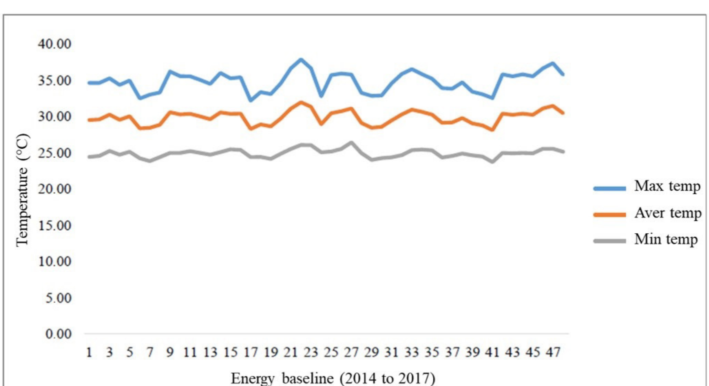

Figure 2. Oscillation of Maximum temperature (Max temp), Average temperature (Aver temp), and Minimum temperature (Min temp) in Boa Vista. Source: INMET (2018).

The case studies examined energy consumption in three private residences, UC1, UC2, and UC3, as well as in the CBV, designated as UC4. The following subsections present the data collected (4.1) and its analysis (4.2), which are crucial steps before proposing solutions to the EE challenges in Roraima.

4.1 Data collection at consumer units and the DPVG source

In case studies, the specific information collected can come from two or more sources of evidence, converging on the same findings (Yin, 2018). In this work, the data collected is quantitative and is associated with direct observation, archival records, and documentation.

4.1.1 Energy situation in the residential sector

Table 3 summarizes the primary information gathered about the three UCs.

Table 3. Information on household characteristics and energy consumption.

Item	Residence 1 (UC1)	Residence 2 (UC2)	Residence 3 (UC3)
Substation	Floresta	Centro	Distrito
Voltage	127/220 V (two-phase)	127/220 V (three-phase)	127/220 V (two-phase)
Circuit breaker	50 A	100 A	40 A
Installed power (Pinst)	15 kW	38 kW	5.4 kW
Total consumption (12 months)	10,630 kWh	20,932 kWh	9,816 kWh
Average monthly consumption	886 kWh	1,744 kWh	818 kWh
No. of residents	2	3	6
Main consumption (installed loads)	Indoor and outdoor lighting (0.5 kW), air conditioning (4.6 kW), refrigeration (0.8 kW), water heating (5.5 kW), and other loads (3.6 kW)	Indoor and outdoor lighting (1.8 kW), air conditioning (6.9 kW) and refrigeration (1.0 kW), electric shower (22.5 kW) and other loads (5.8 kW)	Indoor and outdoor lighting (0.4 kW), air conditioning and refrigeration (3.0 kW) and other loads (2.0 kW)

The installed power (Pinst) of UC2 is higher than that of UC1, which has a higher Pinst than UC3. UC2's Pinst is 60.5% higher than UC1's Pinst. The electrical power (EP) allocated to the cooling loads in UC1 is 5.4 kW (50.8%), while in UC2, it is 7.9 kW (37.7%). In UC3, the smallest Pinst is used by around 55.8%, corresponding to 3 kW, for refrigeration loads. Consumption is due to refrigeration machines, such as air conditioners, refrigerators, and freezers, which are essential for thermal comfort and food preservation. Figure 3 shows households' electricity consumption (EC) ratio over 12 months, from October 2017 to September 2018.

Considering the data provided, although UC2 has a larger Pinst than UC3, the latter uses more equipment simultaneously. Hence, UC3 often operates multiple devices simultaneously, such as two air conditioners, which increases the load factor.

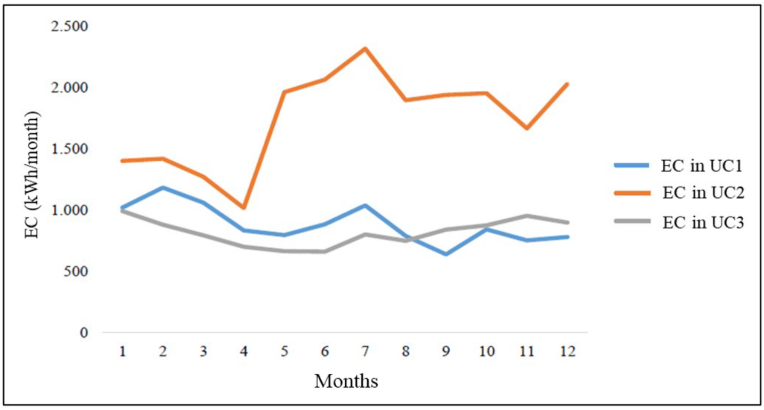

Figure 3. Electricity consumption (EC) ratio between three households in Boa Vista.

4.1.2 Characterization and general conditions of the energy supply at the CBV

The energy supply contract for the CBV stipulates a demand of 500 kW. It operates under the green tariff mode, classified as Public Power, implying a single tariff for power demand in R$/kW. This tariff consists of two parts: one for the peak period and another for the off-peak period, as established by ANEEL. The demand billed to the CBV includes refrigeration machines (split air conditioners, refrigerators, cold rooms), discharge lamps (fluorescent, mixed, mercury vapor, and sodium vapor), and low-power LED lamps. Various other loads present in the laboratories are also considered, such as low-power induction and synchronous motors, motor pumps, automation systems, computers, and printers. According to Table 4, over 48 months, average annual off-peak consumption (OPC) was around 1,288,000 kWh, while average yearly on-peak consumption (PC) was around 129,000 kWh. At the beginning of 2014, the meter did not register energy consumption, leading to many units receiving fixed charges.

Table 4. Peak consumption (PC), off-peak consumption (OPC), and demand (D) in the CBV.

Mo	2014			2015			2016			2017		
	PC (kWh)	OPC (kWh)	D (kW)	PC (kWh)	OPC (kWh)	D (kW)	PC (kWh)	OPC (kWh)	D (kW)	PC (kWh)	OPC (kWh)	D (kW)
Jan	0	76,320	500	6,480	77,760	500	5,369	70,509	500	5,429	61,315	500
Feb	0	113,760	500	9,786	93,022	500	13,844	93,334	545	11,548	87,260	509
Mar	0	121,562	525	10,144	113,365	500	20,823	125,847	579	16,961	112,391	566
Apr	0	112,959	500	10,998	106,262	500	18,700	119,506	648	18,245	115,094	500
Mai	0	102,643	500	10,298	102,331	500	17,436	113,294	594	15,263	105,436	519
Jun	0	120,901	500	10,841	107,688	500	16,368	105,287	517	13,178	91,007	500
Jul	0	115,393	500	10,292	103,439	500	10,218	80,167	500	8,094	63,113	500
Aug	0	114,239	500	12,280	132,081	527	19,224	119,214	534	19,296	109,519	534
Sep	0	133,444	523	12,328	134,332	639	18,307	121,139	594	13,983	123,887	500
Oct	12,329	119,595	521	11,894	143,730	607	18,245	117,626	637	20,089	118,126	560
Nov	12,394	119,723	552	10,530	121,556	573	17,064	121,788	604	18,226	107,993	573
Dec	8,800	101,200	500	8,472	111,201	500	10,231	89,209	533	10,997	80,262	500
Total	33,523	1,351,739		124,343	1,346,770		185,829	1,276,920		171,409	1,175,403	

Source: EDRR (2019).

In addition to this consumption history, measurements were taken at the CBV by the EDRR's technical team, totaling 144 hours (six consecutive days), collecting data every minute. The average power of the installation recorded during the period was around 202.44 kW. The highest power recorded was 488.44 kW in the afternoon, while the lowest was 48.26 kW in the early morning.

Most facilities do not operate on a 24/7 basis. Operations are discontinuous: many do not operate on Sundays and public holidays, and others do not at night or early morning (Filippo, 2018). A CBV's energy consumption profile graph shows the average power use in kW during each period (dawn, morning, afternoon, and night). For example, the campus' average power usage at dawn is 56 kW over 6 hours. The average power multiplied by the use time provides the kWh consumption. The areas indicated in green, red, orange, purple, white, blue, and grey in Figure 4 represent the segmented consumption in kWh of the CBV. Adding these areas together determines the average daily consumption.

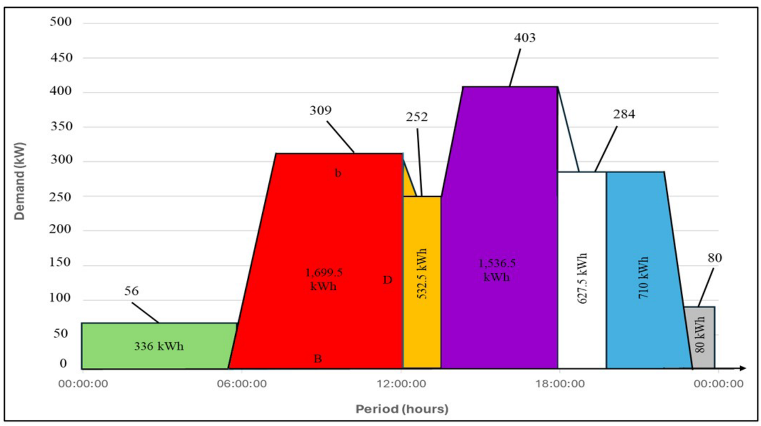

Figure 4. Approximate CBV (UC4) load curve consumption.

ANEEL determines that the installed power is the sum of the nominal powers of the electrical equipment installed in a condition to start operating, expressed in kW. The survey of these loads is essential for knowing the amount of energy at all the consumption points in an installation and is primary for determining the type of supply for a UC. In this case, the load survey sought to identify the Pinst for the CBV's external and internal lighting and the electrical power for the air-conditioning load. Table 5 shows the data for these loads installed in UC4. Other loads, including refrigeration, were not measured.

Table 5. Information on some of the loads installed in UC4.

	External lighting	Internal lighting	Air conditioners
Installed power (Pinst)	108.5 kW	79.9 kW	
Cooling power (CP)			780 kW
Cooling capacity (CC)			8,456,000 Btu/h
Total number of items	116 lamps	1,748 lamps	236 appliances

Source: The authors (2024).

The CBV has a conditioned area of around 9,574 m^2, representing approximately 34.81% of the unit's total covered area of 27,500 m^2. Based on the total refrigeration power and the conditioned area, the organization's refrigeration power per square meter is approximately 0.074 TR/m^2.

4.1.3 Data collection at the CBV's DPVG

The CBV's photovoltaic energy system comprises 270 photovoltaic modules, each rated at 265 Wp/12 V, with dimensions of 1,638 x 982 x 40 mm and a weight of 18 kg. The system includes five electronic inverters, one for each string of 54 modules, capable of generating a direct current voltage of up to 648 V and providing a power output of up to 14.31 kWp (kilowatt-peak), depending on solar radiation. Monitored in real-time via the Fronius Solar website, the system's total capacity is 66 kWp during peak sunshine. The roof area is 1,042 m^2, with the modules covering 434.7 m^2.

Photovoltaic (PV) energy production amounted to 60,395 kWh, while billed electricity consumption (billed CEE) was 900,687 kWh, as shown in Table 6. This data indicates that the CBV's DPVG produced energy equivalent to 6.7% of the billed CEE during the period analyzed, thus impacting the CBV's monthly electricity bill. This impact was most significant in October when photovoltaic energy production amounted to approximately 9,334 kWh, corresponding to 15.46% of PV energy production.

Table 6. Photovoltaic (PV) energy production and billed consumption in the CBV.

Month/Year	String 1 (kWh)	String 2 (kWh)	String 3 (kWh)	String 4 (kWh)	String 5 (kWh)	Production (kWh)	Production (%)	Production PV (%)	Billed monthly CEE (kWh)
Jun/17	261	251	289	284	0	1,085	1.80	1.04	104,285
Jul/17	1,401	907	949	1,374	0	4,631	7.67	6.50	71,207
Aug/17	1,826	1,427	1,829	1,837	1,402	8,320	13.78	6.46	128,815
Sep/17	1,825	1,502	1,893	1,874	1,836	8,929	14.78	6.48	137,870
Oct/17	1,889	1,558	1,910	2,037	1,940	9,334	15.46	6.75	138,215
Nov/17	1,638	1,310	1,697	1,955	1,836	8,434	13.96	6.68	126,219
Dec/17	1,533	1,184	1,589	1,843	1,726	7,874	13.04	8.63	91,239
Jan/18	1,376	1,017	1,425	1,659	1,543	7,020	11.62	17.28	40,618
Feb/18	846	746	1,013	1,115	1,048	4,768	7.89	7.66	62,219
TOTAL	**12,595**	**9,902**	**12,594**	**13,978**	**11,331**	**60,395**	**100**		**900,687**

Source: Fronius Solar (2018).

4.2 Data analysis

This section analyzes the data collected to support the proposals for solving the problems identified.

4.2.1 Energy performance in the residential sector

The data in Table 7 refers to the residences UC1, UC2, and UC3, all operating at a voltage level of 127/220 V. UC1 had an average monthly consumption (AMC) of 886 kWh, exceeding by 2.9 times the average residential consumption (ARC) of Roraima in 2017, which was 306 kWh/month, as recorded in the Electricity Statistical Yearbook (Brasil, 2018b, p. 181). UC2 recorded an AMC of 1,744 kWh, exceeding the ARC by 5.7 times, while UC3 recorded an AMC of 818 kWh, 2.7 times more than the estimated ARC. The data collection period for these residences was from October 2017 to September 2018.

Table 7. Comparison of AMC between residences.

Residence	Built area (m^2)	No. of residents	AMC (kWh)	Pinst (kW)	Refrigeration load (kW)	Protection (A)
UC1	142	2	886	15.0	5.4	50
UC2	360	3	1,744	38.0	7.9	100
UC3	120	6	818	5.4	3.0	40

AMC = Average Monthly Consumption; Pinst = Installed power.

The load for refrigeration machines in UC2 is 7.9 kW, while in UC1, it is 5.4 kW, and in UC3, only 3.0 kW. Electricity consumption in Boa Vista's residential sector is mainly concerned with lighting and refrigeration machines. In Figure 5, the increase in AMC reveals the intense energy use, probably due to the overuse of air conditioners, refrigerators, and freezers.

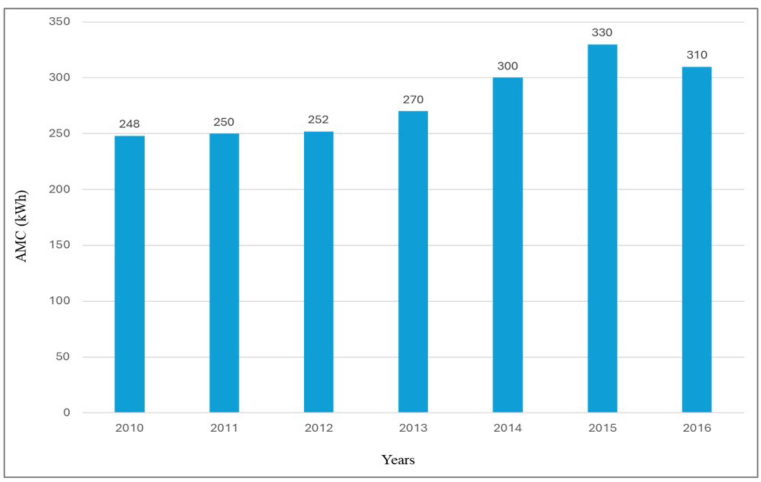

Figure 5. Average Monthly Consumption (AMC) in Roraima from 2010 to 2016.

Residential solar photovoltaic systems contribute significantly to the total share of energy. Developed countries, such as Germany, have created incentive regulations to expand the use of solar systems on buildings. Germany, which pioneered the implementation of feed-in tariffs in the 1990s, established a large base of residential solar systems. This concept was adopted by countries such as the UK, USA, Spain, Italy, and Japan, rapidly expanding their photovoltaic markets (Imam et al., 2019). Residential energy consumption is directly related to average household income per capita, reflecting a higher standard of living and ownership of household appliances and other energy-consuming devices. In Roraima, surprisingly, the average household income "per capita" is the highest in the North region despite Brazil having the lowest Gross Domestic Product (GDP). However, energy consumption is also affected by the average temperature, and the hotter or colder it is, the higher the consumption for general comfort. For example, Boa Vista has the region's highest average temperature, around 30 °C, although many cities in the North and Northeast also have similarly high temperatures (Filippo, 2018).

4.2.2 Energy performance in the CBV (UC4)

Analysis of the CBV's energy performance reveals consumption patterns over the years. Table 8 shows CBV's energy AMC over two periods (four years and three years) for Peak Consumption (PC) and Off-Peak Consumption (OPC) from January to December.

Table 8. AMC at peak and off-peak consumption at the CBV from 2014 to 2017.

Month	PC + OPC (January to December 4 years) (kWh)	AMC (kWh)	PC + OPC (January to December 3 years) (kWh)	AMC (kWh)
Jan	303,182	75,796	226,862	75,621
Feb	422,554	105,639	308,794	102,931
Mar	521,093	130,273	399,351	133,177
Apr	501,764	125,441	388,805	129,602
May	466,701	116,675	364,058	121,353
Jun	465,370	116,343	344,469	114,823
Jul	390,716	97,679	275,323	91,774
Aug	525,853	131,463	411,614	137,205
Sep	557,420	139,355	423,976	141,325
Oct	561,634	140,409	429,710	143,237
Nov	529,274	132,319	397,157	132,386
Dec	420,375	105,094	310,375	103,458

PC = Peak Consumption; OPC = Off-Peak Consumption; AMC = Average Monthly Consumption.

AMC remains practically constant in both situations, at around 118,000 kWh. The lowest consumption occurs in January (around 75,700 kWh), July (around 94,700 kWh), and December (around 104,000 kWh) due to the lower use of loads during recess periods. Figure 6 shows the CBV's AMC over a year, considering the average between columns 3 and 5 of Table 8. There is a seasonal variation in January, July, and December, possibly due to the school calendar and the vacation and recess periods that occur in these months (Filippo, 2016).

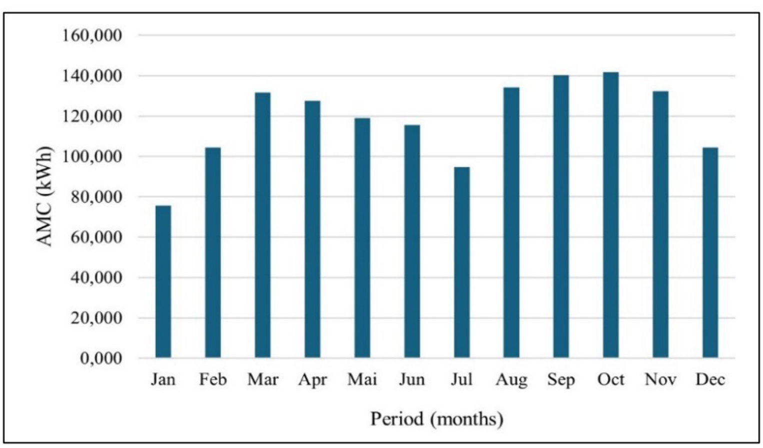

Figure 6. CBV's Average Monthly Consumption (AMC) from 2014 to 2017. Source: Adapted from Filippo (2016).

The CBV's energy supply contract stipulates a demand of 500 kW, which exceeds over 50% of the analyzed months. This data indicates intensive and simultaneous use of installed loads, contributing to excessive energy consumption. Figure 7 shows the graph of the demands measured at the CBV over the 48 months. It shows a pattern of demand oscillating around 500 kW. Consequently, demand at the CBV is consistently high, at or above 500 kW, which may be related to the non-rational use of energy.

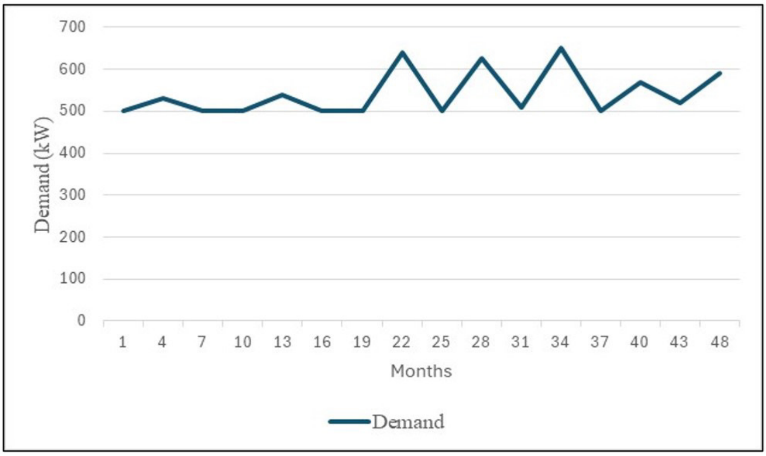

Figure 7. Measured CBV demand over the 48 months (2014 to 2017). Source: Adapted from Filippo (2016).

There are situations in which the level of operation of machines, motors, and equipment depends on factors other than production. For example, in refrigeration and air-conditioning systems, the cooling load can vary markedly depending on the ambient temperature, impacting the energy performance indicator (EPI). In other words, the installation's consumption relates directly to seasonal factors, but it is unclear whether these factors are influenced solely by the calendar, climatic conditions, or both (Filippo, 2018).

4.2.3 Economic feasibility analysis of photovoltaic generation at CBV

The technical and economic feasibility of a 66 kWp DPVG source connected to the local grid, installed at CBV in June 2017 for R$900,000, is evaluated. The financial analysis includes cash flow, payback period, and discounted payback, considering kWh production, savings in reais, minimum attractive rate, internal rate of return, profitability index, and kWh value. Table 9 displays the monthly savings for the six months following the DPVG implementation.

Table 9. Payback cash flow for installing photovoltaics at the CBV.

Year	Month	Energy produced (kWh)	DPVG electrical efficiency (%)	Savings and cash flow
2017	Aug	8,320	12	6,588.71
2017	Sep	8,929	12	7,070.98
2017	Oct	9,334	13	7,391.71
2017	Nov	8,434	13	6,679.00
2017	Dec	7,874	13	6,236.00
2018	Jan	7,020	12	5,559.22
Average value		**8,319**	**12.5**	**6,587.60**

The measurements showed that DPVG produced a total of 49,911 kWh during the analyzed period, resulting in an average of 8,319 kWh, with an average monthly efficiency of 12.5%. The efficiency of a photovoltaic energy source depends on several factors, such as local temperature, which in Boa Vista is around 30 °C, and average irradiation, which in the northern region is 5.5 kWh/m2/day. The average monthly value is 4.89 kWh/m2/day in the horizontal plane (CRESESB, 2018). The payback calculation considered the costs of the materials needed to install and operate a photovoltaic plant like the one installed at the CBV. Unlike technologies that use rotating motion to convert energy, a PV system does not have significant operating costs. However, there are minimal maintenance costs, such as periodic cleaning of the PV modules to remove accumulated dust (Imam et al., 2019).

The payback calculation directly relies on the cash flow presented in Table 9, which was planned based on the energy production of the CBV's photovoltaic source and the reality of Roraima's solar energy potential. Table 10 shows the results of the simple payback, discounted payback, Net Present Value (NPV), profitability index, and internal rate of return (IRR) for each simulated project (P1, P2, and P3). Projects P1 and P2 are unviable due to their negative NPV, while project P3 is viable, with a positive NPV and an IRR higher than the minimum rate of attractiveness. The simple payback indicates a payback time of 11 years, 4 months, and 10 days, while the discounted payback shows a payback time of 35 years, 1 month, and 5 days.

Table 10. Simple and discounted payback of CBV DPVG.

Project	Simple payback	Discounted payback	Profitability index	NPV (R$)	IRR (%)
P1	11 years, 5 months and 19 days	19 years, 2 months, and 12 days	0.999	-852.39	1.09
P2	11 years, 4 months and 19 days	37 years and 8 days	0.994	-5,511.69	2.12
P3	11 years, 4 months, and 10 days	35 years, 1 month, and 5 days	1.139	3,872.09	2.14

NPV = Net Present Value; IRR = Internal Rate of Return.

So, the return on investment will be achieved in 11 years, 4 months, and 10 days, considering the average value of kWh, which in November 2018 had an average annual readjustment of 38.5% (ANEEL, 2018). R$0.7919 per kWh, excluding taxes, was used for simple and discounted payback calculations.

The technical and economic feasibility analysis of a DPVG source installed at CBV, based on 2014–2018 data, reflects market conditions that have changed significantly. Photovoltaic equipment costs have dropped due to technological advancements, the global expansion of solar energy, and evolving public policies and incentives in the renewable energy sector (Zhang et al., 2021). In 2023, the levelized cost of electricity decreased for nearly all energy generation types, except bioenergy and geothermal, with solar photovoltaics— the most widely deployed technology— experiencing the most significant global decline, a 12% drop from 2022. This increasing competitiveness is crucial for tripling sustainable energy capacity by 2030, a key milestone at COP28 to support energy transition objectives and limit global warming to 1.5°C. In 2023, 382 GW of renewable generation capacity—81% of the worldwide increase—produced electricity at costs lower than the cheapest new fossil fuel plants (IRENA, 2024).

These updates are relevant for evaluating the payback of the photovoltaic installation at the CBV in Roraima, considering the current scenario in Brazil. The decline in global equipment costs and the advancement of public policies in the national energy sector can significantly shorten the payback period in the Brazilian context, particularly in regions with high solar incidence, such as Roraima. Changes in energy tariffs, tax incentives, and financing policies for photovoltaic energy also enhance the project's viability, introducing measures not fully available between 2014 and 2018. Since then, solar energy has significantly driven Brazil's clean generation growth. By October 2024, solar installations reached 5,258 MW, representing 57.8% of all new centralized generation capacity (Brasil, 2024a). Compared to the study's initial scenario, current market conditions and public policies make investing in photovoltaic energy an even more economically viable and environmentally sustainable choice.

5 Proposed solutions for energy improvement in Roraima

EE is fundamental to sustainable development and reducing environmental impact. In this context, ANEEL's Energy Efficiency Program (EEP) encourages developing and adopting technologies that increase energy efficiency, benefiting consumers and the electricity sector. Although many EEP initiatives have already been successful, it is essential to adapt the energy generation system to regional particularities, prioritizing clean and economically viable solutions (Brasil, 2024b). Therefore, within the scope of this study, Table 11 presents possible solutions for improving energy use in the state of Roraima, with a view to its evolution in terms of EE and DPVG.

Table 11. Sources of evidence and possible solutions.

Source of evidence	Possible solutions
Electrical projects outside INMETRO standards	Restructure energy projects and adapt the electrical system following INMETRO's RTQ-R for homes and RTQ-C for commercial buildings.
Compensation for losses in Roraima's electricity grid	Implement energy efficiency measures by replacing light bulbs, air conditioners, refrigerators, and freezers.
CBV DPVG surveys	Use DPVG with batteries to stabilize voltage levels affected by varying insolation. It is recommended that batteries with a capacity similar to each photovoltaic module be installed, and a voltage regulator between each battery and module should be included.
Low power quality in the UCs	Filter energy using active filters to eliminate zero-sequence harmonics that overload the neutral conductor, thereby reducing technical losses and avoiding increased consumption.
	Adjust the power factor to a value higher than or equal to 0.92.
	Seek to reduce technical losses and total losses to a value below or near that regulated by ANEEL.
Technical losses observed in the UCs	Modernize the energy metering systems for low and medium voltage units of consumption.
	Reduce technical losses to comply with ANEEL standards, eliminate losses due to the joule effect in outdated transformers, and install bimetallic connectors in copper and aluminum cable branches.
	Advise consumers on electrical losses in residential installations caused by poor-quality equipment and inadequate grounding.

RTQ-R = Technical Quality Regulations for Residences; RTQ-C = Technical Quality Regulations for Commercial, Service and Public Buildings; ANEEL = Agência Nacional de Energia Elétrica.

Initially, it is crucial to standardize the energy systems of homes and public buildings according to INMETRO standards (these standards consider architectural aspects - the envelopes - to improve thermal comfort). In addition, adjustments need to be made to reduce technical losses and ensure that the systems meet the standards regulated by ANEEL. Making these adjustments enables the implementation of improvements in electrical systems to ensure their optimal performance over time. Supervision of the DPVG installation is crucial to avoid thermal losses between the panels, which optimizes energy storage. After implementing the photovoltaic panels, it is essential to guarantee the system's stability, primarily through batteries that can counteract the effects of variations in insolation on the voltage of the photovoltaic source. To date, these batteries have mainly served isolated systems. However, considering the experiences in small communities in the Amazon region and the various implementations in larger-scale systems, it would be pertinent to consider implementing a storage system for part of Boa Vista. Finally, it is essential to educate consumers on the correct use of equipment, encourage the replacement of low-quality or obsolete models, and promote energy efficiency practices. These measures include adopting energy-saving light bulbs, using air conditioners efficiently, and performing regular maintenance on refrigerators and freezers to minimize heat loss. Identifying energy-consuming processes is necessary for optimization (Nabati et al., 2022). In addition, public policies aimed at saving energy are also important.

6 Conclusion

The search for sustainable and practical solutions to meet the energy demands of remote regions, such as the state of Roraima, is a growing priority in the global effort to combat climate change and promote sustainable development. This paper proposes actions to improve energy efficiency in Roraima based on four case studies conducted in three private homes and the CBV. This work fills a gap in the existing literature and answers the research question of ways to improve Roraima's energy performance by promoting sustainable alternatives. The results balance consumption, reduce costs, and promote sustainability. Data analysis revealed problems such as poor electricity quality, inadequate consumption patterns, and outdated equipment that does not meet regulatory standards. Furthermore, installing a DPVG energy source at the CBV has shown that combining energy efficiency improvements with photovoltaic energy sources is an effective solution to mitigate the electricity shortage in Roraima, providing immediate and low-cost benefits.

The main theoretical-scientific contribution of this work is the deepening of knowledge about adopting measures to increase energy efficiency and promote photovoltaic energy generation in developing countries or regions. This contribution strengthens the basis for future discussions on reducing greenhouse gas emissions and advancing this field's state-of-the-art. In terms of managerial-applied contribution, this study creates an opportunity to seek sustainable energy supply solutions for northern Brazil. It also raises questions that can guide public authorities and the private sector on the socio-economic importance of energy efficiency in regions not connected to the SIN. In addition, the study highlights the opportunity to take advantage of the abundant local solar radiation to implement DPVG. Solar radiation is one of the primary sources of clean and renewable energy in the state of Roraima, and it has the potential to address the energy supply problem in various sectors in the short term.

The novelty of this work lies in the combination of academic knowledge about energy efficiency and photovoltaic energy generation with the good initiative developed at the CBV to implement a DPVG. If seen as an example by public authorities, this initiative could become part of an effective strategy aimed at technological development and promoting the rational use of energy in regions facing energy efficiency problems. Future studies could explore the energy consumption of industries and commercial organizations in states in the far north of Brazil. In addition, we suggest increasing public policies aimed at saving energy, especially in regions with high energy consumption derived from non-renewable sources.

Statement on Data Availability

The underlying contents of the research text are contained in the manuscript.

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Authors contribution

Manoel Nascimento Neto and Guilherme Eugênio Filippo Fernandes Filho contributed to conceptualization, investigation, and methodology. Manoel Nascimento Neto performed data curation, which Jorge Muniz Junior validated. Manoel Nascimento Neto, Aglaé Baptista Torres da Rocha, and Otávio José de Oliveira participated in the formal analysis. All authors contributed to the writing—the original draft, manuscript visualization, and validation.