PHOTOVOLTAIC ENERGY: STRATEGIES FOR COST REDUCTION IN PUBLIC EDUCATIONAL INSTITUTIONS

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Abstract

This study evaluates the impact of implementing photovoltaic solar energy systems on reducing electricity costs at a public educational institution located in the northern region of Rio Grande do Sul. Energy consumption data covering a five-year period (2018 - 2023) were analyzed to assess performance before and after the implementation of distributed generation systems. The institution installed photovoltaic plants with a combined capacity of 59.1 kWp, financed through public energy efficiency programs. The results indicate a 45% reduction in off-peak electricity consumption, demonstrating the system's effectiveness in improving energy efficiency and mitigating greenhouse gas emissions. Although external factors - such as tariff adjustments and hydrological crises - affected total energy costs, the photovoltaic installations contributed significantly to reducing grid dependence and increasing operational sustainability. This case study provides evidence of the technical feasibility and socio-environmental benefits of adopting photovoltaics in public institutions, offering insights for policymakers and energy planners aiming to expand the deployment of renewable energy in the education sector and other public infrastructure.

Keywords: Distributed Generation, Electricity Tariffs, Energy Efficiency, Renewable Energy, Sustainability.

1. Introduction

Brazil stands out globally for its extensive use of renewable energy sources. In 2024, solar photovoltaic generation reached 70.7 TWh (centralized generation and MMGD), growing 39.6% compared to 2023 (EPE, 2025). Furthermore, in January 2025, solar energy represented 12.41% of the country's total electricity supply (ABSOLAR, 2025). This rapid growth reflects the country's search for sustainable alternatives to reduce electricity costs, leveraging its favorable solar radiation potential and geographic advantages.

The adoption of renewable technologies in public institutions has been driven both by financial constraints and by environmental commitments. As noted by Oliveira, da Silva, and Altoé (2021), electricity consumption represents a considerable share of the operational budgets of Brazilian universities and technical institutes. Consequently, the implementation of distributed generation (DG) through photovoltaic systems provides a direct and scalable approach to mitigating these expenses while simultaneously fostering a culture of sustainability and energy efficiency within the educational environment.

Beyond the economic benefits, integrating renewable technologies into public institutions also contributes to reducing environmental impacts and carbon emissions. Governmental and institutional programs such as the *Programa de Desenvolvimento em Energias Renováveis e Eficiência Energética nas Instituições Federais de Ensino* (EnergIF) and initiatives from the *Empresa Brasileira de Pesquisa e Inovação Industrial* (EMBRAPII), alongside public tenders promoted by energy utilities, have accelerated the deployment of PV systems in the education sector.

Empirical evidence from several studies - such as Silva et al. (2018), Colombo et al. (2023), and Oliveira (2024) - demonstrates the effectiveness of photovoltaic adoption in public educational facilities, highlighting substantial reductions in electricity consumption and improvements in operational sustainability.

Within this national context, the Federal Institutes of Education, Science, and Technology, which comprise Brazil's Federal Network for Vocational and Technological Education, have played a central role in the

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transition toward cleaner energy models. The IFSul – Passo Fundo Campus, located in southern Brazil, exemplifies this transformation through systematic modernization of its energy infrastructure, including the integration of photovoltaic generation systems and complementary efficiency measures such as the replacement of outdated lighting and air-conditioning technologies.

This study analyzes the electricity consumption profile of a public educational institution in northern Rio Grande do Sul following the installation of photovoltaic systems. The main objective is to quantify the impact of these interventions on energy consumption patterns, cost reduction, and sustainable energy management practices in public educational institutions.

2. Literature Review

2.1. GLOBAL AND BRAZILIAN RENEWABLE ENERGY LANDSCAPE WITH SOLAR PHOTOVOLTAICS

The global energy transition has accelerated significantly in the last decade, with renewable energy technologies becoming essential drivers of decarbonization and sustainable development. In 2024, global cumulative photovoltaic (PV) capacity surpassed 2.2 terawatts (TW), reflecting rapid deployment of solar systems worldwide and consolidating solar photovoltaic as a central pillar in the energy mix (IEA-PVPS, 2025). This expansion was marked by a record addition of more than 550 GW in a single year, with solar accounting for approximately three-quarters of all new renewable capacity installed globally (ABSOLAR, 2025). The scale of this growth underscores the role of PV not only in reducing greenhouse gas emissions but also in reshaping energy systems toward more decentralized, resilient architectures, with distributed generation playing a growing role in key markets such as Germany, Türkiye, and Brazil (IEA-PVPS, 2025; ABSOLAR, 2025).

In Brazil, the rise of solar photovoltaic has been particularly notable. By the end of 2024, the country had reached around 55 GW of installed PV capacity, positioning it among the top 10 solar energy markets globally and ranking 6th in total capacity (ABSOLAR, 2025; pv-magazine International, 2025). This figure includes both distributed generation systems, which comprise most installations connected to the grid, and large-scale PV plants, reflecting a diversification of deployment contexts (pv-magazine International, 2025; IEMA, 2024). The Brazilian PV market has expanded rapidly in recent years, driven by decreasing technology costs, regulatory incentives, and increased participation by residential, commercial, and institutional consumers. Solar photovoltaic now represents one of the fastest-growing sources of electricity in the country and contributes substantially to national efforts to reduce dependence on hydropower and other conventional sources (ABSOLAR, 2025; IEMA, 2024).

Despite this impressive growth at both global and national levels, there remains a gap between current deployment rates and international climate targets. Renewable energy additions, although record-breaking, still fall short of the pace required to triple capacity by 2030 in line with the goals established at the UN climate conferences (REN21, as cited in Reuters, 2025). Nonetheless, the continued leadership of solar PV in capacity additions highlights its critical role in the ongoing energy transition and signals direc-tions for research, policy, and investment to sustain and accelerate this momentum.

2.2. SOLAR PHOTOVOLTAICS IN PUBLIC EDUCATIONAL INSTITUTIONS

The deployment of photovoltaic (PV) systems has become a central element of global strategies to decarbonize energy systems and increase the sustainability of public infrastructure. Among public buildings, educational institutions have gained particular attention as favorable environments for the integration of photovoltaics, offering economic benefits and opportunities for environmental education.

Worldwide, studies have highlighted photovoltaic systems as trends in educational institutions. D'Adamo et al. (2021) investigated a grid-connected photovoltaic system at the University of L'Aquila, Italy, reporting positive net present values and short payback periods when on-site consumption was maximized. Their results are consistent with those of Cucchiella et al. (2018) and Mazzeo et al. (2015), who demonstrated that photovoltaic systems in educational buildings can substantially reduce energy costs and carbon emissions.

Recently, Elum et al. (2024) conducted a technical-economic assessment of photovoltaic systems for Nigerian universities, confirming that the deployment of renewable energy in the education sector increases energy reliability and reduces greenhouse gas emissions.

In Brazil, several studies have evaluated the economic and operational performance of photovoltaic generation in public educational settings. Silva et al. (2018) examined a federal institution in Bahia, demonstrating substantial reductions in electricity consumption and operating costs after the installation of photovoltaic modules. Oliveira, da Silva, and Altoé (2021) showed that universities possess ideal structural and operational conditions for solar deployment, such as large roof areas, predominantly daytime energy demand, and institutional alignment with sustainability goals. Oliveira (2024) further demonstrated that distributed generation in federal institutes promotes cost optimization while strengthening technological development and innovation ecosystems.

Beyond direct financial metrics such as Net Present Value (NPV) and Internal Rate of Return (IRR), recent literature emphasizes the strategic dimension of photovoltaic integration in public institutions. According to the Empresa de Pesquisa Energética (EPE, 2025), solar photovoltaic generation has shown exponential growth in Brazil, reinforcing its structural relevance within the national energy matrix. In this context, distributed generation in educational institutions operates not only as a cost-containment mechanism but also as a resilience strategy against tariff volatility and hydrological crises, which have historically impacted Brazilian electricity pricing.

Additionally, the literature highlights that the effectiveness of PV systems in public institutions depends strongly on load profile compatibility, demand management strategies, and the regulatory framework governing distributed generation compensation mechanisms (D'Adamo et al., 2020; Elum et al., 2024). Institutions with high daytime occupancy and predictable consumption patterns—such as federal institutes and universities—tend to achieve superior technical performance due to improved self-consumption rates, reducing grid dependency and exposure to peak-hour tariffs.

From a sustainability governance perspective, photovoltaic adoption in educational infrastructure aligns directly with the United Nations Sustainable Development Goals (SDG 7 – Affordable and Clean Energy; SDG 13 – Climate Action). Educational institutions thus assume a dual role: they are both energy consumers and agents of socio-technical transformation, fostering awareness, research opportunities, and professional training in renewable energy systems.

Based on this foundation, this study contributes empirical evidence from a long-term analysis (2018–2023) of photovoltaic system performance at a public educational institution in southern Brazil. By integrating billing data analysis, load behavior assessment, and evaluation of distributed generation impacts under real tariff conditions, this research expands the current body of knowledge with applied evidence from the Brazilian Federal Education Network.

2.3. PUBLIC CALLS AND FUNDING PROGRAMS AS DRIVERS OF SOLAR PHOTOVOLTAIC DEPLOYMENT IN PUBLIC INSTITUTIONS

Public funding mechanisms and competitive calls for proposals have become strategic instruments for accelerating the deployment of solar photovoltaic (PV) systems, particularly in public-sector infrastructure. The International Energy Agency (IEA, 2023) highlights that although photovoltaic technology has reached unprecedented cost competitiveness, the initial capital investment remains a structural barrier in institutional settings. In this context, targeted grant programs, green investment funds, and public innovation calls reduce financial risk, enabled generation projects, and accelerate PV integration in buildings with high daytime consumption profiles. The International Renewable Energy Agency (IRENA, 2022) further emphasizes that structured public financing mechanisms significantly increase solar PV adoption rates in emerging economies, especially within educational and governmental facilities.

In Brazil, beyond regulation, the effective implementation of photovoltaic projects in federal universities and institutes has depended heavily on public funding calls and sectoral programs. Initiatives supported by the ANEEL Research and Development Program, the Energy Research Office (EPE), and the EMBRAPII have financed photovoltaic pilot plants, campus-scale distributed generation systems, and applied research in solar energy technologies (EPE, 2025; EMBRAPII, 2023).

From an institutional perspective, public calls for photovoltaic projects operate not merely as financial subsidies, but as structural enablers of solar energy diffusion. Silva et al. (2018) argue that capital-intensive energy infrastructure projects in Brazilian public universities often depend on external funding streams due to fiscal limitations and procurement restrictions. In this sense, solar photovoltaic-specific funding programs contribute to overcoming investment inertia, promoting long-term operational savings, reducing exposure to tariff volatility, and strengthening energy autonomy. Moreover, photovoltaic implementation in educational institutions supported by public calls enhances research capacity, technical training, and innovation ecosystems, transforming campuses into demonstrative environments for solar energy integration. Therefore, competitive funding instruments constitute a decisive policy tool for scaling solar photovoltaic deployment in the Brazilian public sector and consolidating its role within the national energy transition framework.

3. Methodology

This research was conducted through a quantitative and documentary analysis of the electricity consumption profile of a federal educational institution located in southern Brazil. Monthly electricity billing data were collected for a five-year period (August 2018 to August 2023) to evaluate the impact of photovoltaic (PV) system implementation on consumption patterns and cost behavior.

The methodology was structured into three analytical stages:

1. Historical Billing Analysis

Electricity invoices were analyzed to identify:

- Total monthly consumption (kWh).

- Peak and off-peak consumption.

- Contracted demand and measured demand.

- Tariff modality (Green – A4 group).

- Impacts of tariff-flag mechanisms.

This longitudinal approach allowed the identification of structural trends in energy behavior before and after the commissioning of the 18.1 kWp (2019) and 38 kWp (2021) photovoltaic systems, totaling 59.1 kWp of installed capacity.

2. Load Profile and Occupancy Assessment

Peak hours were defined according to the local utility (6:00 PM to 9:00 PM), with the remaining period classified as off-peak.

Occupancy rates were estimated based on institutional records from the Plataforma Nilo Peçanha (2018 - 2022), as shown in Table 1. For 2023, enrollment levels equivalent to 2022 were assumed.

Table 1: Number of registrations per shift (Adapted from the Nilo Peçanha Platform).

Institution	Class schedule (shift)	2017	2018	2019	2020	2021	2022
IFSUL - Passo Fundo	Full-time classes	302	399	496	389	-	52
	Morning	333	362	356	298	515	467
	Afternoon	4	1	45	37	87	238
	Evening	648	677	565	414	515	467

The integration of occupancy indicators with electricity consumption data enabled a contextualized interpretation of load variations, particularly during the COVID-19 pandemic period, when in-person activities were partially suspended. This adjustment was necessary to avoid attributing temporary behavioral reductions exclusively to photovoltaic generation effects.

3. Comparative Distributed Generation Impact Analysis

To isolate the effect of distributed generation (DG), average annual off-peak consumption values were compared between:

- 2019 (pre-full PV implementation baseline)

- 2022 (post-installation stabilized operation).

This comparative methodology is aligned with technical procedures adopted in energy efficiency diagnostics, as recommended in institutional efficiency programs within the Brazilian Federal Education Network. The analysis prioritizes consumption behavior rather than solely financial indicators, considering that tariff readjustments and hydrological surcharges may distort direct economic comparisons.

4. Results and discussions

The analysis of electricity consumption at the public educational institution reveals a demand profile strongly associated with academic occupancy patterns, seasonal climatic variations, and the operational timeline of photovoltaic (PV) systems. Energy use is predominantly concentrated during morning and afternoon periods (off-peak), reflecting the high intensity of in-person teaching activities, laboratory operations, and administrative functions. Evening activities contribute partially to peak-hour demand, particularly due to lighting systems and limited night classes.

The historical behavior of consumption across tariff periods is illustrated in Figure 1, which presents the linear projection of on-peak and off-peak electricity use throughout the analyzed period (2018–2023).

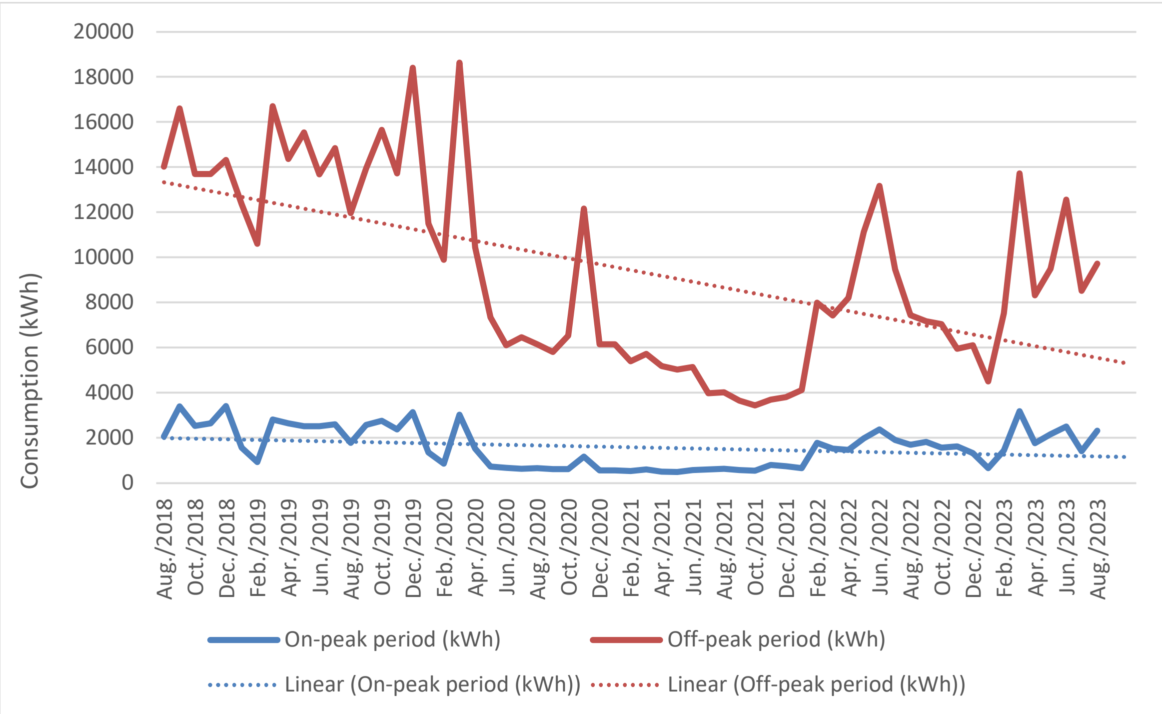

Figure 1: Linear Projection of Energy Consumption (on-Peak and Off-Peak)

As shown in Figure 1, a clear structural inflection occurs after the commissioning of the photovoltaic systems (18.1 kWp in 2019, 38 kWp in 2021, and 3 kWp for educational purposes). Although the COVID-19 pandemic temporarily altered occupancy patterns between March 2020 and March 2022, the post-pandemic consumption levels did not return to pre-2019 baselines, even after the full resumption of in-person activities.

This behavior suggests that the reduction trend is not merely a consequence of reduced occupancy but is structurally linked to distributed generation and energy efficiency interventions implemented during the same period.

Off-peak electricity consumption decreased from 14,312 kWh in 2019 to 7,932 kWh in 2022, corresponding to a 45% reduction, as illustrated in Figure 2.

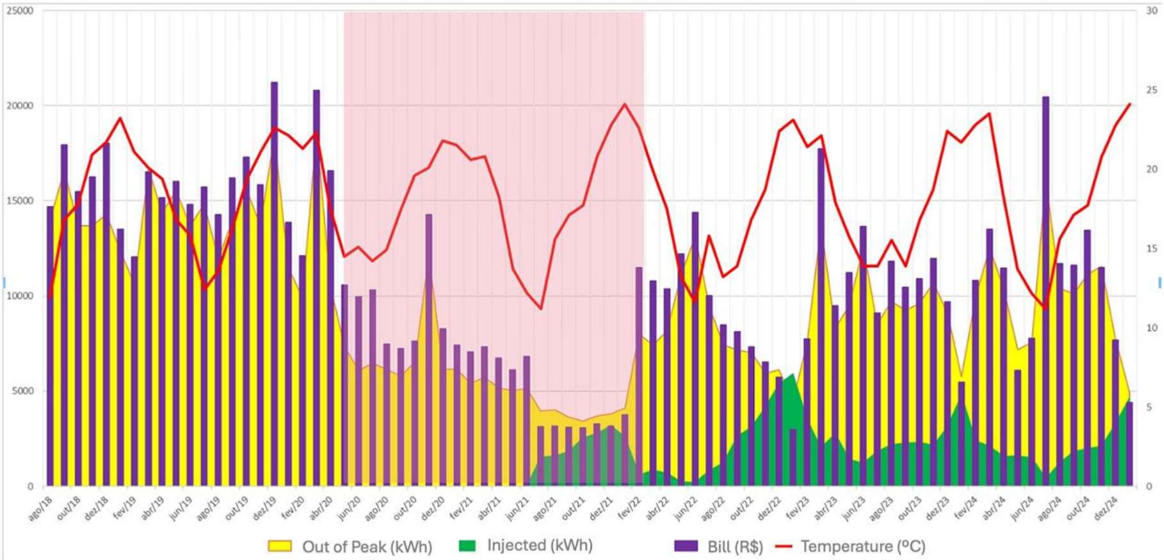

Figure 2: Energy consumption and Energy inject by FV plants compared with local temperature.

Figure 2 further contextualizes the consumption profile by correlating electricity use, photovoltaic energy injection, and average monthly temperature data. A visible seasonal correlation is observed: peaks in consumption coincide with periods of extreme temperatures (both winter and summer), primarily due to HVAC system operation. However, even during high-temperature months, net grid consumption remained consistently lower after PV system implementation.

This result demonstrates two simultaneous dynamics:

1. Structural reduction in baseline demand, attributable to photovoltaic generation and replacement of inefficient lighting and air-conditioning systems.

2. Mitigation of climatic sensitivity, as on-site generation offsets seasonal consumption peaks.

These findings are aligned with previous international case studies (D'Adamo et al., 2021; Elum et al., 2024), which indicate that maximizing self-consumption in educational buildings enhances the economic and technical performance of PV systems. The institution's daytime load profile proved particularly favorable for distributed solar generation, reinforcing the suitability of academic campuses as high-efficiency adoption environments.

However, despite the significant technical reduction in energy consumption, financial savings were partially attenuated by exogenous variables. During the analyzed period, Brazil experienced tariff adjustments, the activation of tariff-flag mechanisms due to hydrological shortages, and the 2021 water crisis, which elevated electricity costs nationwide. Additionally, contractual demand adjustments and tariff modality migration (from Blue-A4 to Green-A4) influenced billing structure independently of consumption reduction.

Therefore, while technical performance indicators demonstrate substantial success, financial outcomes depend not only on energy savings but also on regulatory conditions, tariff dynamics, and demand contract optimization. This reinforces the importance of integrated energy management strategies that combine distributed generation, efficiency measures, and contractual review.

Overall, the empirical evidence confirms that photovoltaic integration reshaped the institution's energy consumption curve, reduced grid dependency, and improved operational sustainability, even under external economic volatility.

5. Conclusion

The integration of photovoltaic systems at the analyzed public educational institution resulted in a measurable and structurally consistent reduction in electricity consumption, particularly during off-peak periods, where a 45% decrease was observed between 2019 and 2022.

Beyond the quantitative reduction in grid energy use, the study demonstrates that distributed generation contributed to reshaping the institution's consumption baseline, reducing seasonal variability impacts, and enhancing operational resilience. The correlation analysis between energy demand and temperature further confirms that on-site solar generation mitigates climate-driven load peaks, reinforcing the technical robustness of the intervention.

Although tariff adjustments and national hydrological crises limited short-term financial gains, the long-term economic trajectory remains favorable. Photovoltaic systems in public educational institutions should not be evaluated solely through immediate billing reduction, but through a broader perspective that includes contract optimization, regulatory adaptation, and lifecycle energy planning.

From a strategic standpoint, this case study reinforces three central conclusions:

- Public educational institutions possess highly compatible load profiles for distributed solar generation.

- Photovoltaic deployment produces structural, not temporary, reductions in energy demand.

- Renewable integration strengthens institutional sustainability, educational engagement, and alignment with SDGs 7 and 13.

In addition, long-term expansion strategies should consider financial structuring mechanisms capable of accelerating renewable energy adoption within the public sector. Finally, the pursuit of funding opportunities through national and international calls for proposals and public grant programs plays a decisive role in enabling Brazilian public educational institutions to expand the use of renewable energy sources such as solar photovoltaic systems, ensuring broader access to technological innovation, infrastructure modernization, and long-term sustainability benefits.

Future research should focus on expanding generation capacity toward partial energy autonomy, integrating real-time monitoring platforms, and applying advanced data analytics to optimize self-consumption rates. Such measures will consolidate photovoltaic energy not only as a cost-reduction mechanism but as a strategic pillar of sustainable public infrastructure management.The integration of photovoltaic systems into public educational institutions demonstrates clear technical benefits, with substantial reductions in off-peak electricity consumption and improved overall energy efficiency. While tariff dynamics and external cost factors can limit short-term financial impacts, distributed solar generation remains a viable long-term strategy for cost control and environmental responsibility.

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