SEVEN
publicações acadêmicas

IMPACT OF THE PUBLIC-PRIVATE PARTNERSHIP FOR PHOTOVOLTAIC SOLAR MINI-POWER PLANTS IN THE STATE OF PIAUÍ ON THE DEPARTMENT OF EDUCATION

IMPACTO DA PPP DAS MINIUSINAS DE ENERGIA SOLAR FOTOVOLTAICA DO ESTADO DO PIAUÍ NA SEDUC

IMPACTO DE LA ASOCIACIÓN PÚBLICO-PRIVADA PARA MINICENTRALES SOLARES FOTOVOLTAICAS EN EL ESTADO DE PIAUÍ EN EL DEPARTAMENTO DE EDUCACIÓN

https://doi.org/10.56238/sevened2025.036-142

Daniel Leal Sousa[1], Marcos Antônio Tavares Lira[2], Albemerc Moura de Moraes[3]

ABSTRACT

The growth in global energy demand, coupled with the environmental impacts caused by non-renewable sources, requires the adoption of public policies aimed at transitioning to renewable sources. In this context, photovoltaic solar energy has stood out as a strategic alternative, especially in regions with high solar incidence, such as the state of Piauí. This study aimed to quantify the economic impact of implementing mini photovoltaic solar power plants within the scope of public-private partnerships (PPPs) in the State of Piauí's Department of Education (SEDUC). The results demonstrated savings in electricity costs (R$ 1,482,184.04 from March 2024 to February 2025). However, important challenges were identified: inadequate initial planning for the allocation of generation credits and delays in the project schedule. It is concluded that the adopted PPP model presents technical and economic viability, but needs adjustments to maximize its social and environmental impacts.

Keywords: Renewable Energy. Sustainability. Energy Demand. Socioeconomic Development. Economic Impact.

RESUMO

O crescimento da demanda energética global, aliado aos impactos ambientais causados pelas fontes não renováveis, exige a adoção de políticas públicas voltadas à transição para fontes renováveis. Nesse contexto, a energia solar fotovoltaica tem se destacado como uma alternativa estratégica, especialmente em regiões com alta incidência solar, como o Estado do Piauí. Esse estudo teve como objetivo quantificar o impacto econômico da implementação das miniusinas de energia solar fotovoltaica no âmbito das parcerias público-privadas (PPP) do Estado do Piauí na Secretaria de Educação (SEDUC). Os resultados demonstraram economia nos gastos com energia elétrica (R$ 1.482.184,04 no

[1] Master of Science in Electrical Engineering. Universidade Federal do Piauí (UFPI).
E-mail: daniel.sousa@ifpi.edu.br Orcid: https://orcid.org/0000-0003-3393-5753
[2] Dr. in Development and Environment. Universidade Federal do Piauí (UFPI).
E-mail: marcoslira@ufpi.edu.br Orcid: https://orcid.org/0000-0002-1691-1488
[3] Dr. of Energy. Universidade Federal do ABC (UFABC). E-mail: albemerc@ufpi.edu.br
Orcid: https://orcid.org/0000-0002-4427-7365

período de março de 2024 à fevereiro de 2025). No entanto, foram identificados desafios importantes: planejamento inicial inadequado da alocação dos créditos de geração e atrasos no cronograma do projeto. Conclui-se que o modelo de PPP adotado apresenta viabilidade técnica e econômica, mas precisa de ajustes para maximizar seus impactos sociais e ambientais.

Palavras-chave: Energia Renovável. Sustentabilidade. Demanda Energética. Desenvolvimento Socioeconômico. Impacto Econômico.

RESUMEN

El crecimiento de la demanda mundial de energía, sumado a los impactos ambientales causados por las fuentes no renovables, exige la adopción de políticas públicas orientadas a la transición hacia fuentes renovables. En este contexto, la energía solar fotovoltaica se ha consolidado como una alternativa estratégica, especialmente en regiones con alta incidencia solar, como el estado de Piauí. Este estudio tuvo como objetivo cuantificar el impacto económico de la implementación de minicentrales solares fotovoltaicas en el marco de asociaciones público-privadas (APP) en la Secretaría de Educación del Estado de Piauí (SEDUC). Los resultados demostraron un ahorro en costos de electricidad (R$ 1.482.184,04 entre marzo de 2024 y febrero de 2025). Sin embargo, se identificaron importantes desafíos: una planificación inicial inadecuada para la asignación de créditos de generación y retrasos en el cronograma del proyecto. Se concluye que el modelo de APP adoptado presenta viabilidad técnica y económica, pero requiere ajustes para maximizar sus impactos sociales y ambientales.

Palabras clave: Energía Renovable. Sostenibilidad. Demanda de Energía. Desarrollo Socioeconómico. Impacto Económico.

1 INTRODUCTION

The world's energy demand is largely met with the use of energy resources of fossil origin, such as oil, coal, and natural gas, which contribute significantly to the emission of greenhouse gases (GHG). The intensive and uncontrolled use of fossil sources (non-renewable) has caused environmental and social impacts of great proportions. Among these impacts, the intensification of global warming, the degradation of air, water and soil quality and health problems in the population stand out. The combustion of fossil fuels is responsible for the massive emission of GHGs, especially carbon dioxide (CO_2), resulting in global climate change. These environmental impacts are of great concern as they compromise the sustainability and well-being of current and future populations (Kibaara and Karweru, 2022).

In view of this alarming context, it is necessary to promote an energy transition, which consists of the gradual replacement of non-renewable sources with renewable energy sources, sustainable and with low environmental impact (Rana et al., 2020).

In this sense, the movement for energy transition is highlighted in multilateral agreements, such as the Paris Agreement, approved in 2015 by 195 countries and the European Union, within the scope of the 21st Conference of the Parties (COP 21). This treaty set ambitious targets for the reduction of global GHG emissions, with the aim of limiting the increase in the Earth's average temperature to less than 2 °C compared to pre-industrial levels (Meinshausen et al., 2022).

In parallel, also in 2015, the United Nations (UN) instituted the Sustainable Development Goals (SDGs), as part of the 2030 Agenda. This global agenda aims to guide actions by governments, companies, and civil society towards sustainable development by the year 2030 (UN, 2025).

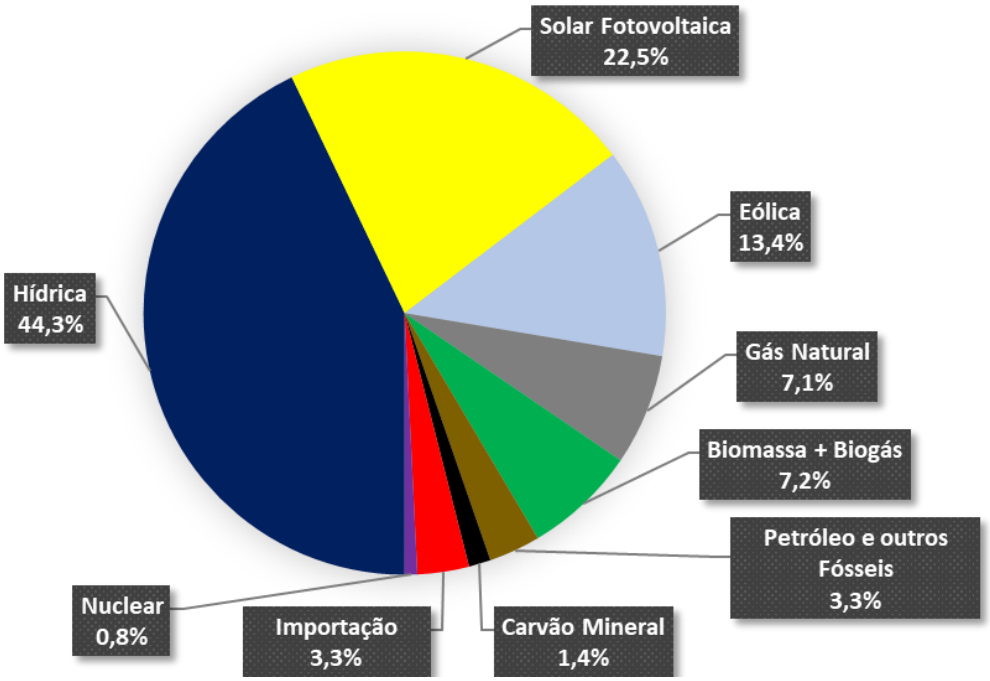
In line with this perspective, several scholars point out that the current energy model, based predominantly on non-renewable sources, has become incompatible with the sustainable development goals established by the 2030 Agenda, especially with regard to SDG 7, which seeks to ensure reliable, sustainable, modern, and affordable access to energy for all (Saccardo et al., 2023).

In Brazil, the growing consumption and socio-environmental impact caused by traditional energy sources (hydroelectric plants, which flood a large area to store water, and thermoelectric plants that produce GHGs by burning fossil fuels) have led the government and society to think of new alternatives for generating electricity (Sousa et al., 2023). The

Brazilian electricity matrix (Figure 1) is mostly dependent on hydroelectric generation, which corresponds to 44.3% of the total (EPE, 2025). However, due to the irregular rainfall regime, the country faces recurrent water crises, which are also reflected in energy crises.

Figure 1

Brazilian Electricity Matrix



Source: Prepared by the author with data from (EPE, 2025).

The search for sustainable and low-GHG energy alternatives is necessary to promote sustainable development (Mele et al., 2021; Dai et al., 2024). Corroborating this perspective, Lira et al. (2019) highlight that photovoltaic solar energy also has additional advantages, such as the absence of direct GHG emissions in the generation process, the reduction of electrical losses, given the proximity of generation to consumer centers, and the reduction of dependence on thermal plants.

In view of the intensification of the problems resulting from the climate crisis, there is an expansion of debates and initiatives aimed at the development and adoption of new energy matrices, among which solar energy stands out (Hecksher, 2024). In Brazil, there is a significant expansion of energy generation through photovoltaic solar sources. This advance was driven by the publication of Normative Resolution No. 482, of April 17, 2012, of the National Electric Energy Agency (ANEEL), which established rules for the insertion of distributed generation in the country and by the favorable scenario of solar irradiation,

especially in the northeast region, with emphasis on the State of Piauí (Rocha & Barra Neto, 2024; Pereira et al., 2017).

The State of Piauí has high potential for generating electricity from photovoltaic solar sources, due to its geographical location in one of the regions with the highest levels of solar radiation in Brazil (Morais et al., 2025). The sectors that most use the photovoltaic solar source for electricity generation are the residential and commercial sectors. On the other hand, the public sector is the one with the lowest percentage of energy generation through solar energy, evidencing the need for more investments aimed at expanding the use of renewable sources (EPE, 2025).

In this context, public-private partnerships (PPPs) emerge as a strategic model of cooperation between the public sector and the private sector, in which both assume responsibilities, risks, and investments in the implementation of projects of collective interest. PPPs have the ability to attract private investments to the sector, so the government is able to dilute the payment of the counterpart over time, without having to invest a high amount. This type of partnership enables the mobilization of private capital for the development of energy projects, while promoting the optimization of public resources. In the electricity sector, PPPs have the potential to accelerate the adoption of photovoltaic technology, contributing to the diversification of the energy matrix, the expansion of installed renewable generation capacity, and the reduction of government spending on the payment of electricity bills (Awuku et al., 2022).

Cooperation between the public and private sectors is essential for strengthening the capacity to generate photovoltaic solar energy. Such initiatives contribute not only to the expansion of installed capacity, through the implementation of photovoltaic systems of different sizes, but also to the promotion of sustainable growth, in line with global guidelines for energy transition and decarbonization of the electricity matrix. International organizations, such as the World Bank, highlight that PPPs are effective instruments to accelerate technological development, reduce investment costs, and mitigate risks associated with the expansion of generation from renewable sources (World Bank, 2023).

Based on this model, the Government of the State of Piauí instituted, in 2018, the Piauí Clean Energy Development Program – PROPIDEL to prepare the project "Public-Private Partnership for the implementation, operation and maintenance of Solar Energy Mini-Plants".

The project was divided into 4 lots, in the form of an administrative concession for the construction, operation, maintenance and management of photovoltaic solar energy generation mini-plants, with management and operation of electricity credit compensation services, and the construction of two mini-plants per lot was planned (SUPARC, 2024).

Mini-plants help promote the energy transition and reduce dependence on non-renewable sources. This project is a pioneering example of PPP in this area. The main objective of the mini-plants is to meet the energy demand of the Government of the State of Piauí (SUPARC, 2024). The generation of electricity through photovoltaic solar sources increases the availability of power in the SIN, reduces electricity expenses and reduces the environmental impacts caused by non-renewable sources. This use directly contributes to the achievement of the Sustainable Development Goals (Soares et al., 2023).

To contribute to the energy transition process and to the strengthening of sustainable development, this work carries out a study of the impacts caused by the implementation of photovoltaic solar energy mini-plants built through PPPs to meet the energy demand of SEDUC in Piauí. The research seeks to answer the following scientific problem: how these mini-plants can contribute to the reduction of SEDUC's electricity costs, promote local socioeconomic development and what are the best guidelines to improve and expand the use of this technology in the context of PPPs.

Understanding these impacts is crucial to justify and optimize investments in renewable energy, aiming at sustainable development and more efficient energy management in the State. The main hypothesis raised was that the implementation of mini-plants can reduce electricity costs and the amount saved can be applied in actions that promote environmental conservation and local social development.

2 METHODOLOGY

The methodological steps include bibliographic review, survey and analysis of public data, development and application of interviews and questionnaires, as well as technical visits.

To obtain a solid theoretical basis on PPPs, renewable energies and mini solar photovoltaic plants, a literature review was carried out. The research was conducted in the academic databases: Brazilian Digital Library of Theses and Dissertations (BDTD), Capes Journal, Scopus, Web of Science and Google Scholar, using combined keywords (solar energy, PPP, socio-environmental impact, economic impact, mini-plants, renewable energy,

sustainability and infrastructure) with the connectors "AND" and "OR". The same keywords were used in English to broaden the search following the methodology used by Xue et al. (2021). After the initial filtering, a critical analysis was carried out on the scientific articles and technical reports found.

To obtain the data related to the mini-plants and the SEDUC of Piauí, which receives the generation credits, those responsible for them were contacted. The requests were made by different means of communication (e-mail, telephone contact, WhatsApp and request protocol directly in the SEDUC protocol sector). The electricity bills (covering the period of 12 months), the list of consumer units that receive the credits with the percentages allocated to each one and the monthly amount paid for the generation of the mini-plant were requested.

With the data from electricity bills, it is possible to compare energy costs, comparing the amounts that would be paid without generation with the amounts paid with the compensation of credits to calculate and evaluate the economic impact.

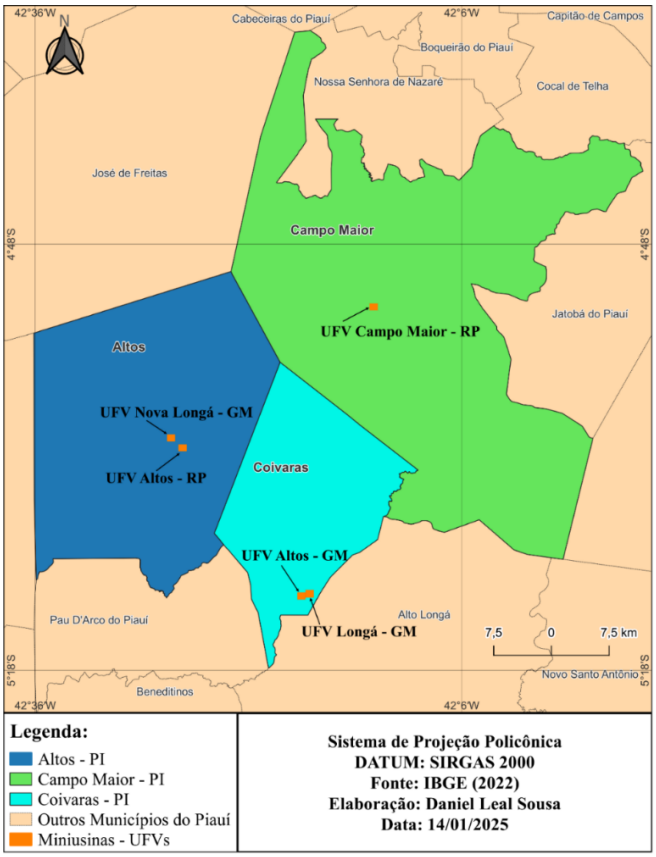
The combination of these methodological steps allowed a comprehensive and interdisciplinary analysis of the impacts of photovoltaic solar power plants in the scope of PPPs in the State of Piauí. The results obtained contribute to the development of guidelines aimed at improving the implementation of these projects, maximizing the benefits.

2.1 DELIMITATION AND CHARACTERIZATION OF THE STUDY AREA

The area delimited for the study comprises the locations where the mini photovoltaic solar energy plants are installed in the State of Piauí through PPPs of the State Government. These mini-plants represent an important milestone in the development of renewable energy generation in the region (SUPARC, 2024). A total of five photovoltaic solar generation mini-plants were built in three municipalities in the State of Piauí: Altos, Coivaras and Campo Maior (Figure 2).

Figure 2

Location map of the five mini-plants built

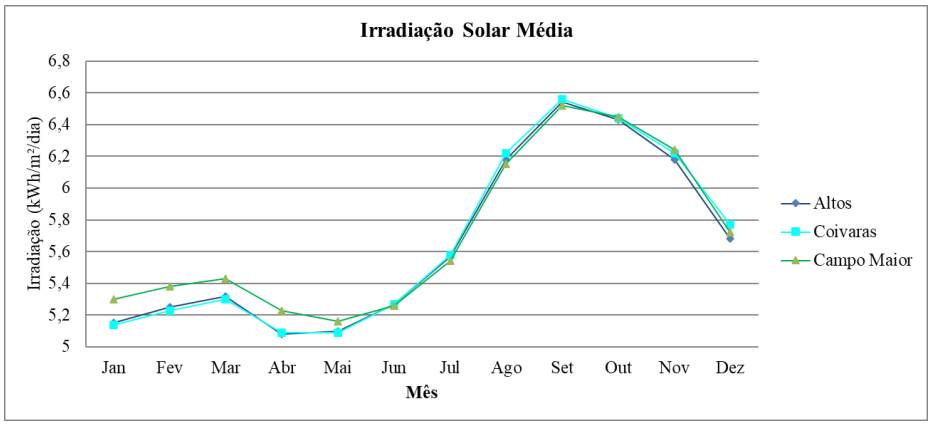


Source: Prepared by the Author

The choice of these three municipalities was justified by the high level of solar radiation in these locations, which are among the municipalities with the highest rates of solar irradiation in the State of Piauí (Pereira et al., 2017). Such a climatic condition significantly favors the performance of photovoltaic plants, maximizing their generation and reducing the payback time of investments. Figure 3 shows the graph with the average solar irradiation indices in the municipalities of Altos, Coivaras and Campo Maior in (kWh/m².day).

Figure 3

Average solar irradiation in the municipalities of Altos, Coivaras and Campo Maior in Piauí



Source: Prepared by the Author with data from EPE (2025)

3 RESULTS AND DISCUSSIONS

In this section, the main results and the respective discussions will be presented.

3.1 MINI-PLANTS CONTRACTED BY SEDUC

One of the mini-plants was installed in the municipality of Altos – PI (UFV Nova Longá), with the following coordinates of the installation site: latitude: -5.028271; longitude: -42.439764. UFV Nova Longá, has an installed capacity of 1,350 kW and was connected to Equatorial Piauí's distribution network in April 2023. The plant's infrastructure consists of 2,673 bifacial photovoltaic modules of the TSM-650DEG21C.20 model, with a unit power of 650 Wp, totaling a peak power of 1,737.45 kWp. To convert the energy generated, six TBEA – TS228KTL-HV inverters were installed, with a power of 225 kW each. It uses a support structure with a solar tracking system (*tracker*), which makes it possible to monitor the movement of the sun throughout the day, increasing efficiency in capturing solar radiation. The company responsible for the execution of the project and installation of the system was NETLUX Solar.

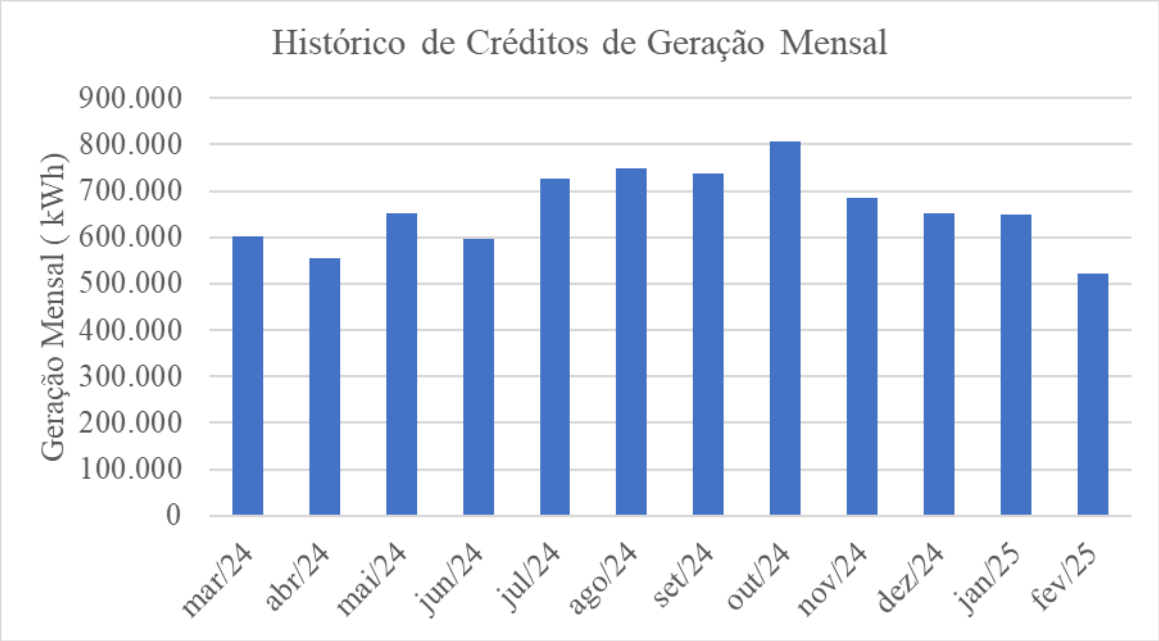
The other unit was installed in Coivaras - PI (UFV Longá), with the following coordinates of the installation site: latitude: -5.213587; longitude: -42.284163. The Longá UFV also has the same characteristics as the Nova Longá UFV with different amounts of modules and inverters. It has an installed power of 1,800 kW, consisting of 3,663 photovoltaic modules of 650 Wp, resulting in a total peak power of 2,380.95 kWp. The system has eight TBEA – TS228KTL-HV inverters, with a capacity of 225 kW per unit and

also uses *trackers*. The connection of the plant to the grid of the concessionaire Equatorial Piauí was carried out in May 2023, installed by NETLUX Solar.

The history of electricity generation of the two mini-plants in the period between March 2024 and February 2025 is outlined in Figure 4. It is observed that the months of July 2024 to November 2024 are the months in which we have the highest generation of electricity. This is due to the solar irradiation being higher in these months of the year, as we can see in the solar irradiation graph in Figure 3.

Figure 4

History of electricity generation in kWh of the mini-plants, UFV Nova Longá and UFV Longá, which serves SEDUC built from contract 04/2020



Source: Prepared by the author with data from . (SUPARC, 2024)

The contract signed between SEDUC and GM ENERGIA foresees that these two mini-plants should generate an average of 650,000 kWh per month. The contract also specifies a minimum monthly generation value that is 5% below the contracted average, that is, 617,500 kWh at least.

If the generation supplied does not reach the amount contacted, the company must pay a fine, in addition to the reduction of the amount paid in the month for the generation of the mini-plant. The amount contracted for the monthly purchase of the mini-mill's production was set at R$ 387,000.00 (three hundred and eighty-seven thousand reais) in 2020, the year the contracts were signed, and this amount is readjusted by the IPCA each

year. In this way, the secretariat increases the predictability of electricity expenses. In 2025, this amount was corrected by the IPCA, as provided for in the contract and was set at R$ 514,427.06 (five hundred and fourteen thousand, four hundred and twenty-seven reais and six cents).

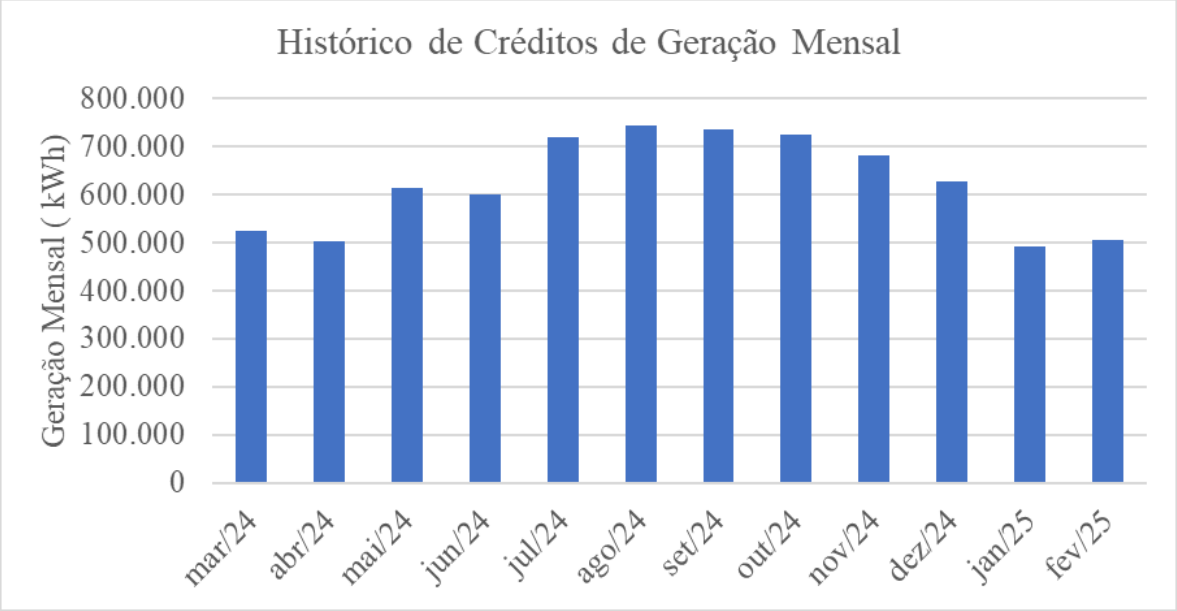
In the municipality of Altos – PI, we have another mini-plant installed (UFV Altos) built by RIO POTI ENERGIA, to meet the energy demand of SEFAZ. After the start of operation, it was found that the generation of electricity by the mini-plant was much higher than SEFAZ's electricity demand, for this reason this unit was ceded to SEDUC in March 2024.

This photovoltaic minigeneration installation has a nominal capacity of 2,895 kW, and is located in the municipality of Altos – PI. The coordinates of the mini-plant installation site are: latitude: -5.040073; Longitude: -42.427166. It has an installed power of 2,895 kW, and is composed of 7,068 bifacial photovoltaic modules of the RSM110-8-540BMDG model, manufactured by RISEN SOLAR, each with a power of 540 Wp, totaling a peak power of 3,816.72 kWp. It has 13 215 kW inverters and one 100 kW inverter, all from the manufacturer HUAWEI, models SUN2000-215KTL and SUN2000-100KTL, respectively and also has a *tracker*. The connection to the grid of the concessionaire Equatorial Piauí was completed in May 2023. The estimated energy production for this mini-plant is approximately 7,800,000 kWh per year or 650,000 kWh per month.

The history of electricity generation of this mini-plant in the period between March 2024 and February 2025 is outlined in Figure 5.

Figure 5

History of electricity generation in kWh of the mini-plants built from contract 08/2020



Source: Prepared by the author with data from . (SUPARC, 2024)

The contract signed between SEDUC and RIO POTI ENERGIA provides that this mini-plant should generate an average of 650,000 kWh per month and has the same specifications as the contract with GM Energia. In the year 2024, the amount paid per month by SEDUC for the monthly consideration of contract 08/2020 is R$ 484,858.52 (four hundred and eighty-four thousand, eight hundred and fifty-eight reais and fifty-two cents). In 2025, this amount was corrected by the IPCA, as provided for in the contract and was set at R$ 511,129.44 (five hundred and eleven thousand, one hundred and twenty-nine reais and forty-four cents).

Until 2023, SEDUC had 35 collective electricity invoices and currently these invoices have been regrouped into 3 collective invoices:

- ✓ Invoice for units served at low voltage, group B.
- ✓ Invoice for units served in medium voltage, group A.
- ✓ Invoice of the administrative center unit in Teresina – PI, group A.

The units of GROUP A pay cheaper for the kWh consumed during off-peak hours (from 8:30 pm to 5:29 pm), so it is not so feasible to offset the consumption of these units with the generation credits of the mini-plants.

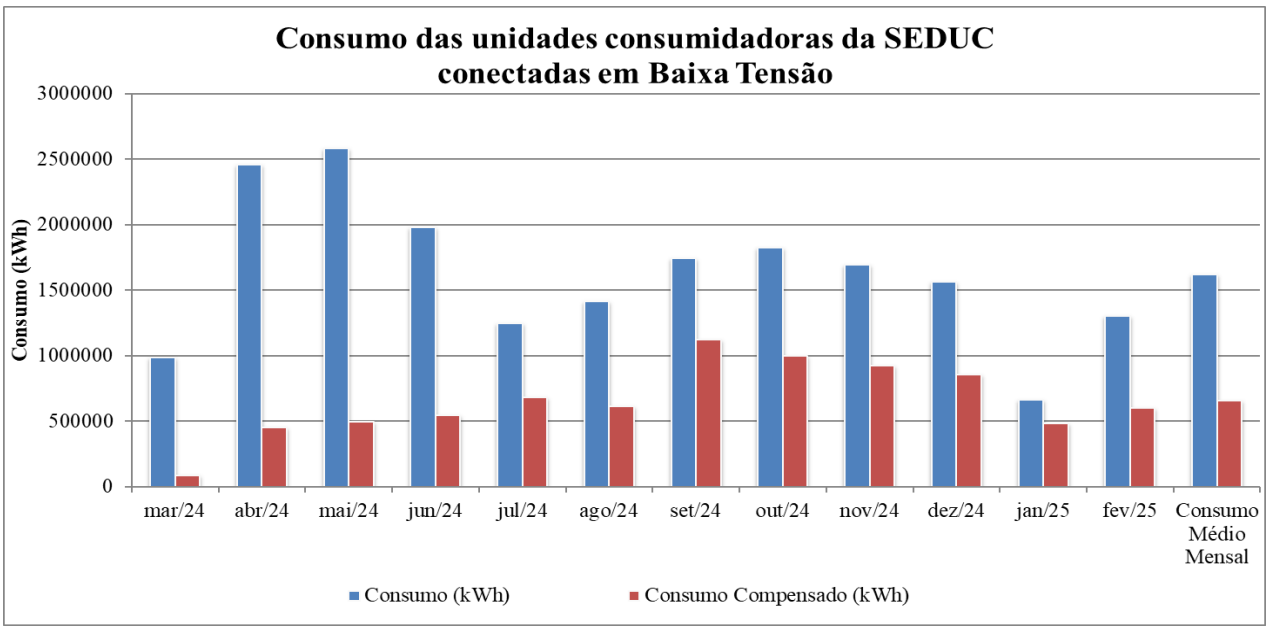
Analyzing the consumer units belonging to SEDUC, we obtain a total of 1,046 consumer units. Of this total, 124 are classified in group A and 922 are in group B. The

demand contracted by SEDUC at the headquarters in the administrative center is 700 kW and in the other 123 units of group A it is 9,944 kW.

The average monthly consumption of SEDUC units connected to low voltage (Group B) considering the period from March 2024 to February 2025 is 1,623,045 kWh per month. Regarding the average consumption compensated per month, there is a value of 656,268 kWh/month. This indicates that approximately 40.4% of the total consumption of these units was compensated. The history of energy consumption in kWh and compensated consumption can be seen in Figure 6.

Figure 6

Consumption history of SEDUC consumer units connected to Low Voltage



Source: Prepared by the author with data from SEDUC

The total electricity consumption recorded by SEDUC's low voltage units was approximately 19,476,542 kWh, resulting in an average monthly consumption of 1,623,045 kWh. This consumption value represents an expressive and continuous demand for electricity, compatible with the decentralized functioning structure of the state school network, which covers 922 consumer units distributed throughout the territory of Piauí.

The variability observed between the months reinforces the need for a dynamic strategy for the allocation of distributed generation credits, which takes into account the cycles of higher and lower demand. Even without the variation in allocation, the compensation is benefited because the excess credits in a month have up to 5 years to be

used. The maintenance of a monthly average of more than 1.6 GWh reinforces the potential for economic gains arising from an efficient energy compensation, especially considering the high tariffs applied to low-voltage consumer units.

In this context, the generation from photovoltaic mini-plants represents a strategic instrument to reduce electricity costs, and it is essential that credits are allocated preferentially to this group, which has high consumption and high higher cost per kilowatt-hour, compared to units connected to medium voltage. The prioritization of low-voltage units in SEDUC's energy compensation policy allows maximizing the financial benefits of the PPP, contributing to the fiscal sustainability of the public administration and to the fulfillment of the SDG targets, in particular SDG 7 and SDG 12.

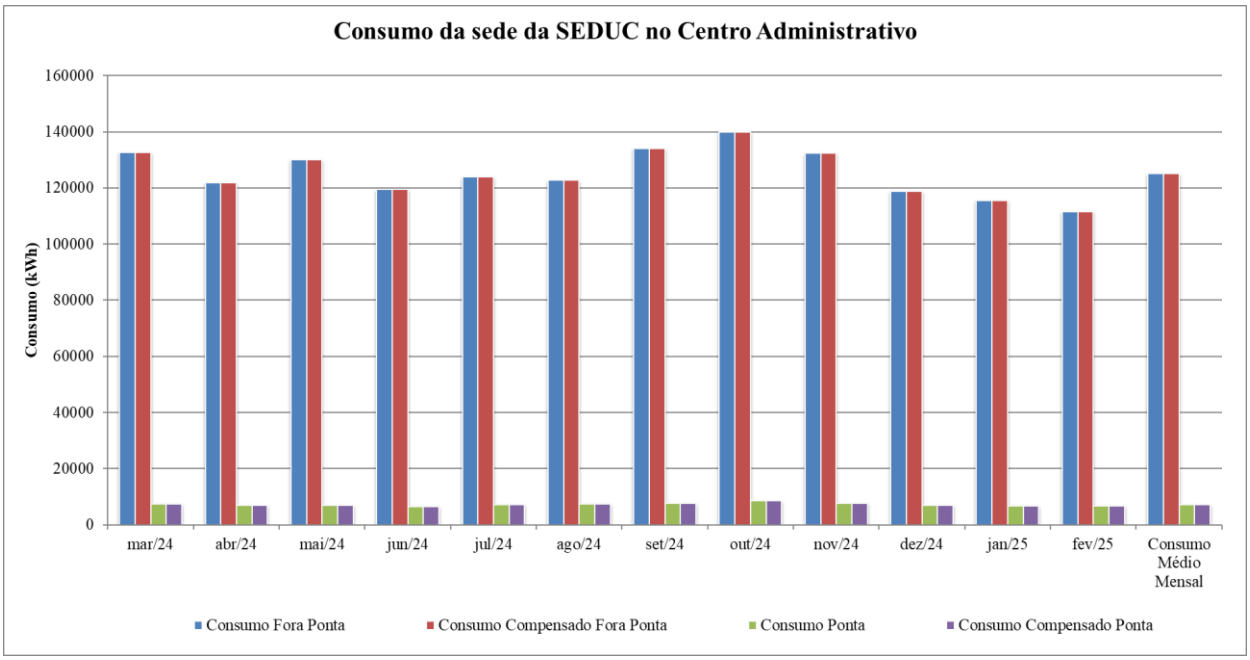
The consumption pattern verified in the low voltage units of SEDUC shows both the high demand and the opportunity to increase the economic efficiency of the distributed generation project, through energy planning that considers the seasonal specificities of the state school network and optimizes the allocation of available electricity credits.

The analysis of the energy consumption of the Headquarters Unit of the State Department of Education (SEDUC), located at the Administrative Center in Teresina – PI, from March 2024 to February 2025, reveals that the unit had a total consumption of 1.59 GWh, with a monthly average of 132,403 kWh. Most of this consumption occurred during off-peak hours, totaling 1.50 GWh, while 86,349 kWh were recorded during peak hours. It is observed that consumption was fully compensated with generation credits over the twelve months (Figure 7), resulting in a compensation percentage of 100%.

Although this result of offsetting all consumption may seem to be the ideal scenario, a critical evaluation is necessary from the perspective of economic optimization of credit allocation. The Headquarters Unit is connected to medium voltage, which implies lower energy tariffs than those applied to low-voltage consumer units. In practical terms, the cost avoided by offsetting thirst consumption is significantly lower than the cost avoided by offsetting the same volume of power in low-voltage units.

Figure 7

Consumption history of the SEDUC Headquarters in the Administrative Center



Source: Prepared by the author with data from SEDUC

Thus, the full allocation of generation credits to the Headquarters Unit, although technically effective, is not the best strategy from a financial point of view. The ideal model, in terms of maximizing the tax savings generated by the PPP, consists of prioritizing the compensation of low voltage units, whose energy is priced at higher values, thus ensuring a more significant financial return for each kWh compensated. The Headquarters Unit, in turn, must be compensated only when there is a surplus of generation credits after all units of the grid connect to low voltage.

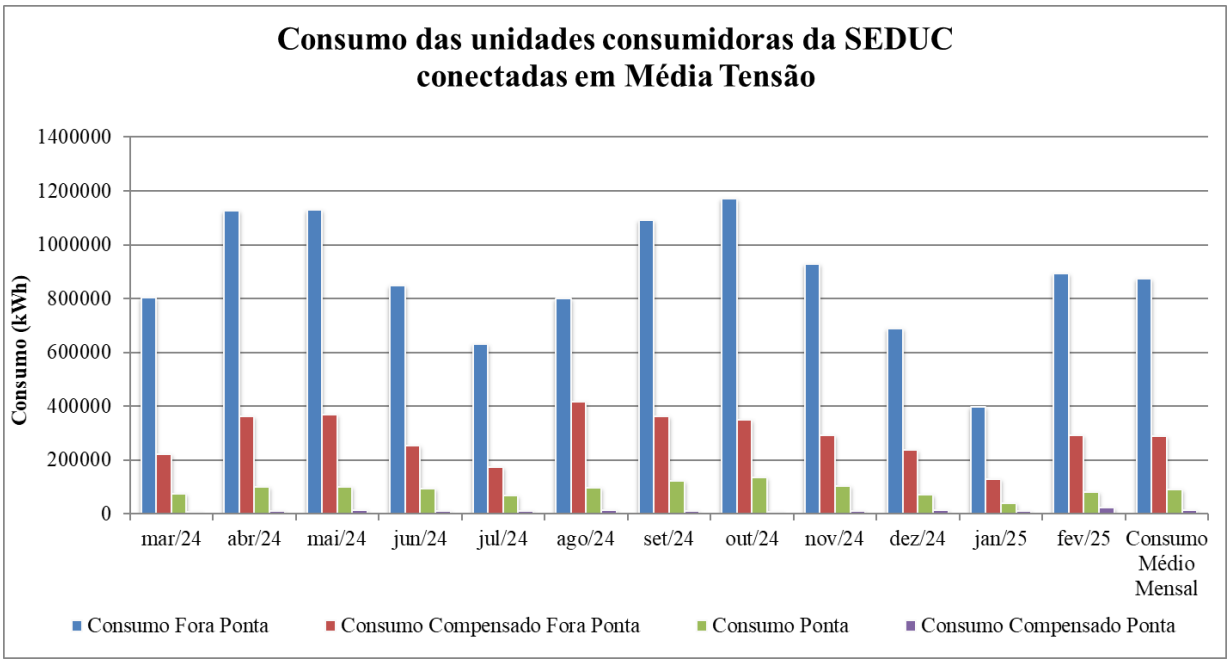
Adopting this strategy of hierarchical allocation of credits (with prioritization based on the cost of energy) would maximize the economic impact of the distributed generation project, enhancing the savings provided by the PPP and reinforcing the financial sustainability of the public policy.

It is observed, therefore, that the decision to fully compensate the consumption of the Headquarters Unit, although operationally viable, does not represent the best practice in terms of public energy policy, given the current tariff structure. The analysis recommends reviewing the strategy for allocating generation credits, based on economic and tariff criteria, in order to ensure the maximum effectiveness of the PPP in meeting the principles of economy, efficiency and sustainability, as recommended by the SDGs.

The evaluation of the energy consumption of the SEDUC units connected to medium voltage during the period analyzed, shows that the medium voltage units recorded a total consumption of 11,599,502 kWh, with a monthly average of 966,625 kWh. Of this total, 3,617,887 kWh were effectively compensated, resulting in an average compensation index of 31.36%. Although this percentage can be considered modest, it should be interpreted with caution: medium voltage units, despite their high absolute consumption, as already mentioned in the consumption analysis of the SEDUC headquarters unit, have a lower value charged per kWh than low voltage units. Thus, each kWh compensated in this group generates a lower financial return for the public administration. Figure 8 shows the monthly consumption in the period analyzed.

Figure 8

Consumption history of SEDUC consumer units connected to Medium Voltage



Source: Prepared by the author with data from SEDUC

In this context, maintaining or expanding the compensation of these units, while there is still a significant deficit of compensation in low-voltage units (which pay higher tariffs), does not represent the most efficient allocation of available generation credits. The analysis of the data shows that low voltage units, despite representing a relevant portion of consumption, have been partially compensated (on average 43%), maintaining monthly deficits above 960,000 kWh.

Therefore, from the perspective of maximizing the economic benefit of the PPP, the ideal would be that all generation credits from mini-plants should be allocated primarily to low-voltage units. Only after the full compensation of this group should the eventual surplus be directed to medium voltage units. This allocation logic respects the principle of economy and seeks the highest possible financial return per unit of energy compensated.

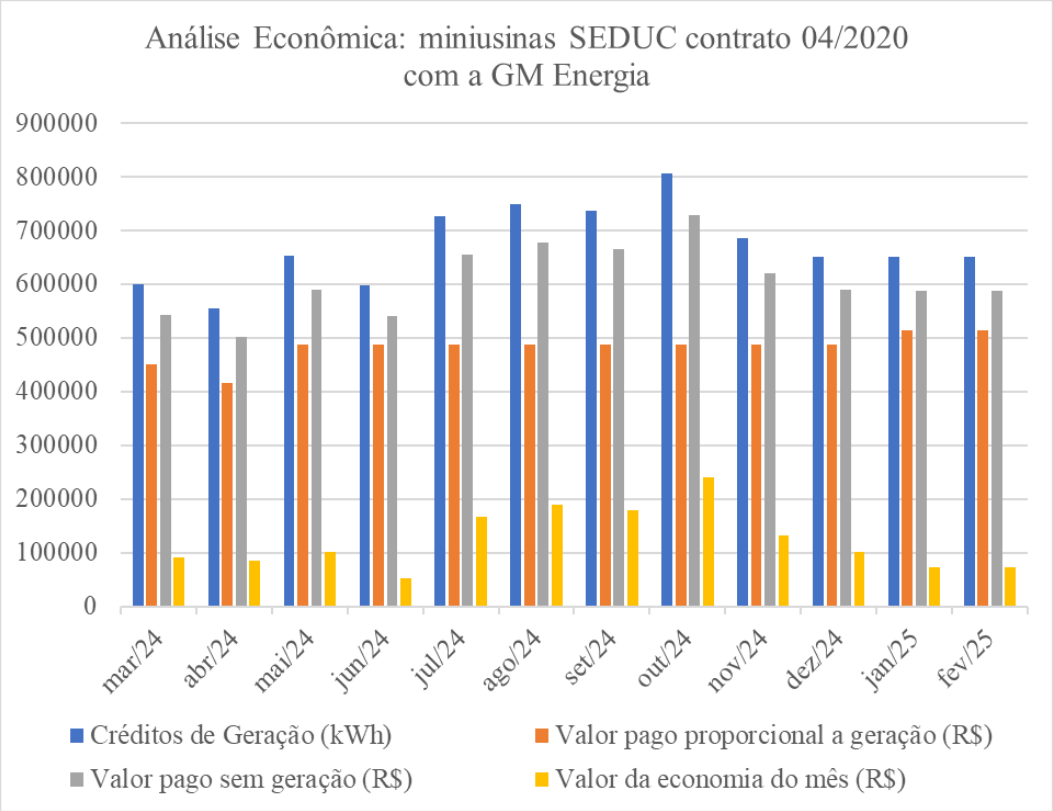
To analyze the economic impact, the amount paid monthly to the companies of the mini-plants was compared and the amount that would be paid without generation credits was calculated. The analysis was made for the credits of each contract. Figure 9 shows the history of offset credits for the mini-plant of contract 04/2020 and the amounts paid to the company proportional to the generation received and the amount that would be paid to Equatorial Piauí without considering the generation credits.

Based on the data presented in Figure 9, it is possible to identify savings in electricity expenses, directly reflecting the positive effects of distributed generation.

In the period from March 2024 to February 2025, the energy compensation resulted in a total saving of R$ 1,482,184.04, which is equivalent to an average monthly saving of approximately R$ 123,515.34. This amount represents the difference between what would be paid by SEDUC in a scenario without its own generation and the amount actually paid proportional to the volume of energy compensated with credits from the mini-plants.

Figure 9

History of offset generation credits and amounts paid for generation credits related to contract 04/2020



Source: Prepared by the author with data from SEDUC

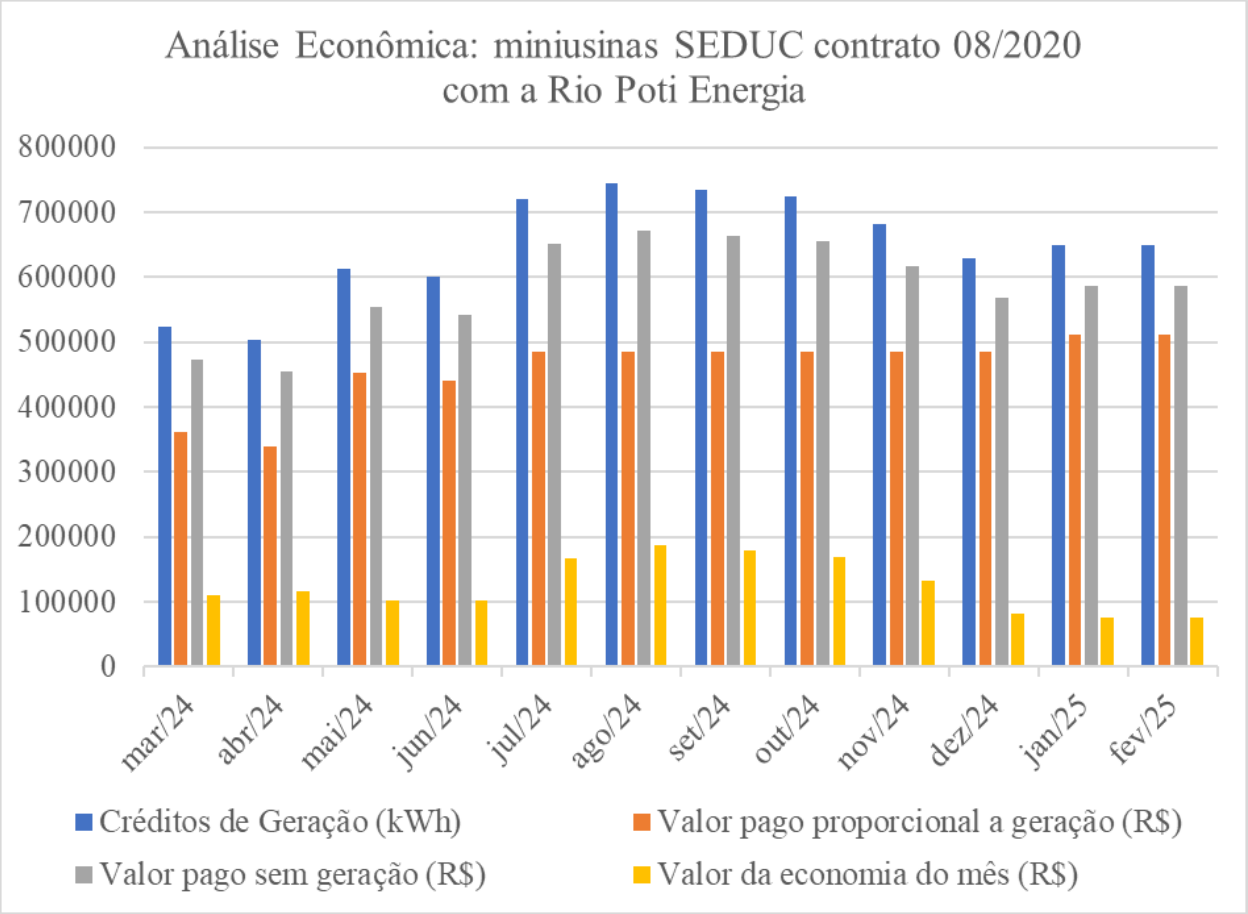
The month with the highest savings was October 2024, with an amount saved of R$ 239,671.61. It is observed that the months with the lowest savings were the months of January and February 2025. This reduction in savings occurred due to the reduction in the value of the energy tariff by Equatorial and the increase in the amount to be paid for the monthly consideration to the company, which is corrected by the IPCA every year.

The savings generated are particularly relevant considering the context of growing operating expenses of the public administration with electricity. In addition, it is a recurring saving, which is renewed with each billing cycle and contributes to the relief of the public budget, without compromising the quality of the services provided by the school units.

The same analysis was also carried out for the mini-plant of contract 08/2020, as can be seen in Figure 10.

Figure 10

History of offset generation credits and amounts paid for generation credits related to contract 08/2020



Source: Prepared by the author with data from SEDUC

In the period analyzed, the energy compensated by the plants linked to contract 08/2020 enabled a total saving of R$ 1,499,163.08, which corresponds to an average monthly saving of R$ 124,930.26. This saving is calculated as the difference between what would be disbursed without the use of generation credits and the amount actually paid proportional to the compensated consumption.

The month with the greatest savings was August 2024, when the amount saved reached R$ 187,234.30, possibly due to higher photovoltaic generation associated with the peak of solar irradiance and the good allocation of credits to units with higher tariff costs.

These results confirm the effectiveness of Contract No. 08/2020 as a public policy tool for reducing current expenses with electricity. The recurring monthly savings obtained over a budget year provides not only tax relief, but also the opportunity to redirect resources

to other areas of education, such as school infrastructure, food, transportation, or teacher training.

4 CONCLUSION

The energy transition to renewable sources, especially solar photovoltaics, is an urgent need in the face of the climate and environmental challenges that the world is facing. In Brazil, and particularly in the State of Piauí, the potential for solar energy generation is great, as it has high levels of solar radiation all year round, but it is still underutilized.

The government must lead this energy transition policy for the use of renewable sources. PPPs are vital instruments to assist this transition, significantly increasing the contribution of generation through renewable sources by the government, offering a collaborative model that can help overcome the financial and technical obstacles that limit the expansion of renewable energy energy.

From a technical point of view, it can be proven that the performance of the mini-plants was satisfactory, with all units managing to reach the contracted value of average monthly generation of 650,000 kWh. All installations have *tracker technology*, which allows the photovoltaic modules to be directed according to the position of the sun to increase the facility's generation capacity. These mini-plants were the first to be installed in the state of Piauí with this type of mechanism.

Regarding the economic analysis, the implementation of the mini-plants resulted in significant savings in the energy bills of the secretariat. The savings generated between March 2024 and February 2025 (12 months) totaled R$ 1,482,184.04, with a monthly average of R$ 123,515.34. The peak of savings was observed in October 2024, with R$ 239,671.61 saved, while the lowest amount occurred in February 2025, reflecting tariff adjustments by the distributor and contractual correction of the consideration.

The analysis of consumption at the SEDUC Headquarters Unit, located in the administrative center in Teresina, revealed a total of 1,588,830 kWh consumed in the 12-month period, of which 1,502,481 kWh occurred during off-peak hours and 86,349 kWh during off-peak hours. All consumption was offset with generation credits, reaching 100% offset. However, the total compensation of the Headquarters unit, connected to medium voltage, proved to be financially less advantageous than the compensation of the units in low voltage, whose tariff is higher. Thus, it was found that the strategy of compensating all with consumption of the headquarters unit, from an economic point of view, is not the best

option. Initially, all units connected to low voltage must be compensated and only compensate the consumption of units served at medium voltage if there are still generation credits left.

However, the project also highlighted structural problems and challenges that compromise its efficiency. The main one was the lack of planning taking into account the energy demand of each government agency that benefited. The inadequate initial allocation of generation from the mini-plant contracted to the Department of Finance (SEFAZ), for example, whose monthly demand was lower than the contracted generation capacity, was one of the main problems found. This distortion was corrected with the transfer of the generating unit to SEDUC, with compatible demand, but the episode revealed flaws in prior planning and in the estimation of the real demand of public agencies.

Piauí's experience in implementing solar mini-plants via PPP is successful in terms of technical feasibility and contribution to the energy transition. However, maximizing its benefits requires greater integration between technical planning, local public policies, and social engagement. The replication and expansion of this model depends on strengthening governance, improving demand diagnostics, and adopting inclusive strategies that consolidate environmental and social gains with affected communities. Such measures can amplify the positive effects of PPPs, consolidating mini-plants as effective instruments of energy, environmental and social public policy.

REFERENCES

Awuku, S. A., Bennadji, A., Muhammad-Sukki, F., & Sellami, N. (2022). Public-private partnership in Ghana's solar energy industry: The history, current state, challenges, prospects and theoretical perspective. Energy Nexus, 6, Article 100058. https://doi.org/10.1016/j.nexus.2022.100058

Dai, L., Shen, J., & Zhang, F. (2024). Development status and application analysis of new energy photovoltaic power generation energy market based on artificial intelligence. International Journal of Low-Carbon Technologies, 19, 351–358. https://doi.org/10.1093/ijlct/ctae009

Empresa de Pesquisa Energética. (2025). Dados abertos. https://www.epe.gov.br/pt/publicacoes-dados-abertos/dados-abertos

Hecksher, C. B. M. da C. (2024). Políticas públicas e usinas solares: Indicadores socioeconômicos e percepção da população em municípios de Minas Gerais. ARACÊ, 6(4), 13835–13866. https://doi.org/10.56238/arev6n4-165

Kibaara, S., & Karweru, M. (2022). Developing a techno-economic modelling tool for small scale utility solar PV technology for quantifying environmental impacts. 2022 IEEE 7th

International Energy Conference (ENERGYCON) (pp. 1–6). https://doi.org/10.1109/ENERGYCON53164.2022.9830267

Lira, M. A. T., Melo, M. L. da S., Rodrigues, L. M., & Souza, T. R. M. de. (2019). Contribution of photovoltaic systems connected to the electrical network for reducing CO2 in the state of Ceará. Revista Brasileira de Meteorologia, 34(3), 389–397. https://doi.org/10.1590/0102-7786343046

Meinshausen, M., Lewis, J., McGlade, C., Gütschow, J., Nicholls, Z., Burdon, R., Cozzi, L., & Hackmann, B. (2022). Realization of Paris Agreement pledges may limit warming just below 2 °C. Nature, 604(7905), 304–309. https://doi.org/10.1038/s41586-022-04553-z

Mele, M., Gurrieri, A. R., Morelli, G., & Magazzino, C. (2021). Nature and climate change effects on economic growth: An LSTM experiment on renewable energy resources. Environmental Science and Pollution Research, 28(30), 41127–41134. https://doi.org/10.1007/s11356-021-13337-3

Morais, F. H. M. de, Lira, M. A. T., & Lopes, W. G. R. (2025). Solar and groundwater resources assessment for the installation of photovoltaic pumping systems in the state of Piauí, Brazil. Groundwater for Sustainable Development, 29, Article 101443. https://doi.org/10.1016/j.gsd.2025.101443

Organização das Nações Unidas. (2025). Objetivos de desenvolvimento sustentável. https://brasil.un.org/pt-br/sdgs

Pereira, E. B., Martins, F. R., Gonçalves, A. R., Costa, R. S., Lima, F. J. L. de, Rüther, R., Abreu, S. L. de, Tiepolo, G. M., Pereira, S. V., & Souza, J. G. de. (2017). Atlas brasileiro de energia solar (2nd ed.). Universidade Federal de São Paulo. https://doi.org/10.34024/978851700089

Rana, R. L., Lombardi, M., Giungato, P., & Tricase, C. (2020). Trends in scientific literature on energy return ratio of renewable energy sources for supporting policymakers. Administrative Sciences, 10(2), Article 21. https://doi.org/10.3390/admsci10020021

Rocha, Á. G., & Barra Neto, A. (2024). Economia circular na fotovoltaica: Uma análise das regulamentações globais e suas implicações no Brasil. ARACÊ, 6(3), 5590–5613. https://doi.org/10.56238/arev6n3-080

Saccardo, R. R., Domingues, A. M., Battistelle, R. A. G., Bezerra, B. S., Siqueira, R. M., & Neto, J. B. S. dos S. (2023). Investment in photovoltaic energy: An attempt to frame Brazil within the 2030 passage target of the Paris agreement. Cleaner Energy Systems, 5, Article 100070. https://doi.org/10.1016/j.cles.2023.100070

Soares, C. A. B., Nadae, J. de, Nascimento, D. C. do, Firmino, P. R. A., & Morioka, S. N. (2023). Photovoltaic solar energy and sustainability in higher education institutions: A multiple case study. Revista Gestão da Produção Operações e Sistemas, 18, 103–135. https://doi.org/10.15675/gepros.v18i00.2939

Sousa, D. L., Silva, O. A. V. de O. L. da, Morais, F. H. M. de, Lira, M. A. T., Moraes, A. M. de, & Alves, D. R. da S. (2023). Economic feasibility of distributed generation for Brazilian households: Influence of the new legal framework. Revista Brasileira de Ciências Ambientais, 58(1), 134–144. https://doi.org/10.5327/Z2176-94781574

Superintendência de Parcerias e Concessões. (2024). Miniusinas de energia solar. http://www.ppp.pi.gov.br/pppteste/index.php/projetos/estudo-de-viabilidade/miniusinas-de-energia-solar/

World Bank. (2023). The PPP reference guide version 2.0. https://www.worldbank.org/en/topic/publicprivatepartnerships/publication/the-ppp-reference-guide-version-20

Xue, Y., Lindkvist, C. M., & Temeljotov-Salaj, A. (2021). Barriers and potential solutions to the diffusion of solar photovoltaics from the public-private-people partnership perspective – Case study of Norway. Renewable and Sustainable Energy Reviews, 137, Article 110636. https://doi.org/10.1016/j.rser.2020.110636