

**JUST ENERGY TRANSITION IN THE AMAZON: ECONOMIC AND
SUSTAINABLE ANALYSIS OF ALTERNATIVE ENERGY SOURCES FOR
RIVERSIDE COMMUNITIES**

**TRANSIÇÃO ENERGÉTICA JUSTA NA AMAZÔNIA: ANÁLISE ECONÔMICA E
SUSTENTÁVEL DE FONTES ALTERNATIVAS PARA COMUNIDADES
RIBEIRINHAS**

**TRANSICIÓN ENERGÉTICA JUSTA EN LA AMAZONÍA: ANÁLISIS
ECONÓMICO Y SOSTENIBLE DE FUENTES ALTERNATIVAS PARA
COMUNIDADES RIBEREÑAS**

 <https://doi.org/10.56238/sevened2025.036-025>

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ABSTRACT

Access to safe and sustainable electrical energy is an essential element for socio-economic development, particularly in remote regions of the Brazilian Amazon. This paper carries out a comparative cost-benefit analysis of three electrification alternatives: off-grid photovoltaic systems, diesel generators, and informal network, based on a case study in the riverside community of Nazaré, Abaetetuba-PA. Employing tools from economic engineering and sustainability metrics, the study evaluates implementation, operational, and maintenance costs, as well as nets present value, cost per kWh generated, and environmental impact. The findings indicate that, although requiring higher initial investments, off-grid photovoltaic systems demonstrate greater economic efficiency in the long term and have a lower socio-environmental impact. This makes them a viable solution for low-income communities, highlighting the potential of solar energy as a strategic approach to energy inclusion. The study supports efforts to reduce inequalities and promote a just energy transition, aligning with Sustainable Development Goals (SDGs 7, 10, and 13).

Keywords: Sustainability. Solar Energy. Energy Access. Riverside Communities. Economic Analysis.

RESUMO

O acesso à energia elétrica de forma segura e sustentável é um elemento essencial para o desenvolvimento socioeconômico, especialmente em regiões remotas da Amazônia brasileira. Este estudo realiza uma análise comparativa do custo-benefício de três fontes alternativas de eletrificação, sistemas fotovoltaicos off-grid, geradores a diesel e redes clandestinas, com base em um estudo de caso realizado na comunidade ribeirinha de

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Nazaré, no município de Abaetetuba-PA. Utilizando ferramentas da engenharia econômica e parâmetros de sustentabilidade, são avaliados os custos de implantação, operação e manutenção de cada sistema, além do valor presente líquido, custo do kWh gerado e impacto ambiental. Os resultados demonstram que, apesar do maior investimento inicial, os sistemas fotovoltaicos apresentam maior eficiência econômica a longo prazo e menor impacto socioambiental, tornando-se uma solução viável para comunidades de baixa renda. O estudo reforça o papel da energia solar como alternativa estratégica para a inclusão energética, contribuindo para a redução das desigualdades e para a promoção de uma transição energética justa, em consonância com os Objetivos de Desenvolvimento Sustentável (ODS 7, 10 e 13).

Palavras-chave: Sustentabilidade. Energia Solar. Inclusão Energética. Comunidades Ribeirinhas. Análise Econômica.

RESUMEN

El acceso a electricidad segura y sostenible es esencial para el desarrollo socioeconómico, especialmente en regiones remotas de la Amazonia brasileña. Este estudio realiza un análisis comparativo de costo-beneficio de tres fuentes alternativas de electrificación: sistemas fotovoltaicos aislados, generadores diésel y redes eléctricas ilegales. Este análisis se basa en un estudio de caso realizado en la comunidad ribereña de Nazaré, en el municipio de Abaetetuba, Pará. Utilizando herramientas de ingeniería económica y parámetros de sostenibilidad, se evalúan los costos de implementación, operación y mantenimiento de cada sistema, junto con su valor actual neto, costo por kWh generado e impacto ambiental. Los resultados demuestran que, a pesar de la mayor inversión inicial, los sistemas fotovoltaicos ofrecen mayor eficiencia económica a largo plazo y menor impacto socioambiental, lo que los convierte en una solución viable para comunidades de bajos ingresos. El estudio refuerza el papel de la energía solar como alternativa estratégica para la inclusión energética, contribuyendo a la reducción de las desigualdades y a la promoción de una transición energética justa, en línea con los Objetivos de Desarrollo Sostenible (ODS 7, 10 y 13).

Palabras clave: Sostenibilidad. Energía Solar. Inclusión Energética. Comunidades Ribereñas. Análisis Económico.

1 INTRODUCTION

Access to electricity is a fundamental pillar of sustainable development, directly impacting essential dimensions such as health, education, food security, and social mobility (FAISAL et al., 2024). Several studies point out that the availability of reliable energy is associated with poverty reduction, income generation, and the promotion of social inclusion (RAJABRATA et al., 2021); (ALEX et al., 2021). On the other hand, the absence or precariousness of this resource is a critical obstacle to economic progress, especially in developing countries (AIGHEYISI et al., 2020), where the challenge of energy poverty highlights deep territorial and social inequalities.

In Brazil, this scenario is particularly pronounced in the North and Northeast regions, which historically have the lowest rates of access and consumption of electricity (GALVÃO et al., 2020); (THIVES et al., 2022). The Amazon, although rich in biodiversity and natural resources, is home to thousands of communities excluded from the National Interconnected System (SIN), as is the case of approximately 400 thousand people who live on the banks of rivers in areas of difficult access, often also deprived of the full exercise of citizenship (COSTA and VILLALVA, 2020).

Although universalization programs such as "Luz para Todos" (Decree No. 7,520/2011) have promoted advances, efforts to expand conventional electricity infrastructure still do not include more remote communities (DA SILVA et al., 2024); (LEDUCHOWICZ-MUNICIO et al., 2024). In the municipality of Abaetetuba-PA, for example, islands such as Sirituba and Campopema received transmission lines, while others, such as Guajará and Nazaré, remain on the margins of public policies, facing logistical and economic barriers to conventional electrification (SEGURA-SALAS et al., 2022).

Faced with this scenario, excluded communities have resorted to alternative solutions, such as clandestine electricity networks, usually pulled from neighboring municipalities, and diesel generators (HENAO and GUZMAN, 2024). However, these options are marked by instability, voltage fluctuations, and frequent interruptions (POPA, 2022), compromising the safety and durability of household equipment and information systems, such as internet providers. In addition, the burning of fossil fuels aggravates environmental impacts and represents a setback compared to global goals for reducing greenhouse gas emissions (GANI, 2021).

The adoption of off-grid Photovoltaic Systems (off-grid SFV) emerges, in this context, as a promising and sustainable alternative, capable of meeting basic demands in a clean,

autonomous, and economically viable way in the medium and long term (HASSAN, 2021). Such solutions align with the principles of the just energy transition, by ensuring access to quality energy for historically neglected populations, while minimizing environmental impacts and promoting greater local resilience.

This study proposes a comparative economic analysis between different alternatives of electric generation, solar photovoltaic, Diesel Generators (DG) and clandestine grids, based on a case study in the riverside community of Nazaré, in Pará. The objective is to evaluate, from the perspective of sustainability, which of the options offers the best performance in terms of cost-benefit, supply stability and socio-environmental impacts. In this context, the research seeks to develop innovative approaches to estimating the cost of electricity in communities isolated from the conventional electricity grid, considering not only the economic aspects, but also the social and environmental effects of each solution. It is also intended to offer technical support to engineering professionals, public managers and policymakers, through economic analysis tools integrated with sustainability criteria. The comparison between the generation alternatives aims to demonstrate the financial impacts on the budget of low-income families, as well as the associated environmental consequences, especially in the case of diesel generators and clandestine networks, still common in the northern region of Brazil. Finally, the research highlights the potential of solar energy as a vector of sustainable development and social inclusion, contributing to the mitigation of energy inequalities and the promotion of a fair energy transition, in alignment with the Sustainable Development Goals (SDGs), particularly numbers 7, 10 and 13.

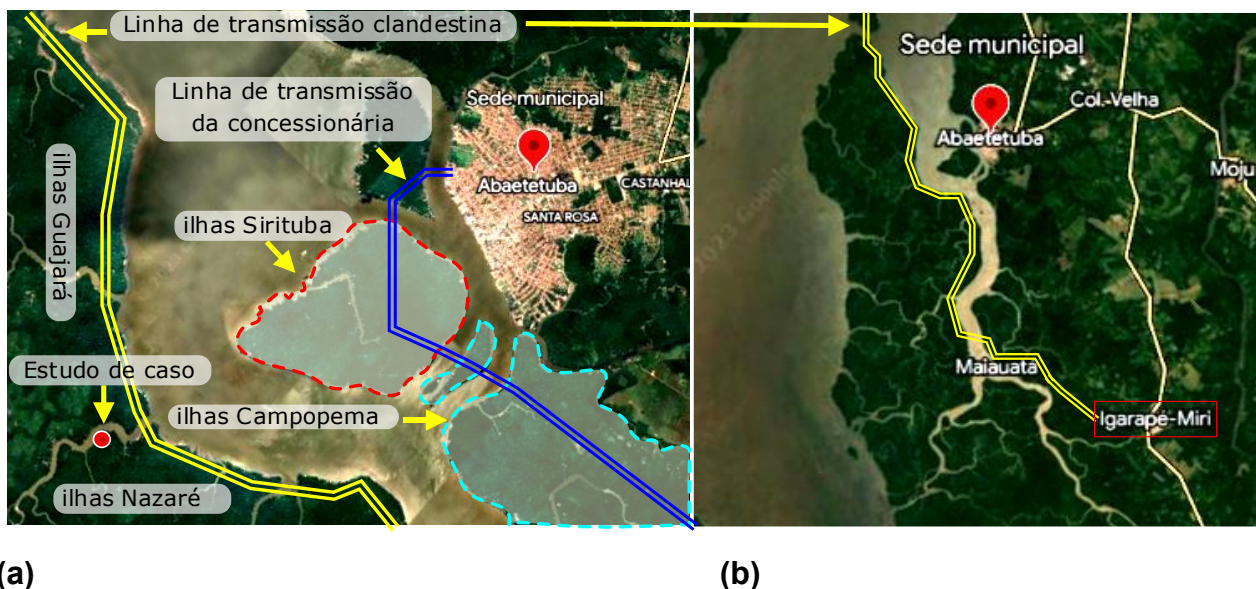
2 PRELIMINARY STUDIES

2.1 ESTIMATION OF THE ELECTRICAL LOAD IN THE COMMUNITY

The Maracapucú River, one of the main watercourses in the municipality of Abaetetuba-PA, is divided into two sections: Maracapucú-Miri and Maracapucú-Grande, which are home to the islands of Nazaré and Guajará, respectively. The present study was conducted on Nazaré Island, which has an estimated population of 1,278 inhabitants, including young people, adults and children. The main local economic activities include family farming, artisanal production and the management of açaí, a fundamental basis of riverside subsistence. The island has approximately 580 residences distributed along its length. The specific area of analysis was a village located on the margins of Nazaré Island, about 1 km away from the urban center of Abaetetuba-PA, as illustrated in Figure 1.

Figure 1

Location of the community and transmission lines: (a) municipal headquarters and community, (b) path of the air lines



Source: Prepared by the authors.

The village consists of seven residences, all built within the standards established by a federal government housing program, which defines uniform design and dimensioning characteristics. Figure 2 illustrates one of the housing units belonging to this complex, located in that community.

Figure 2

Village house (reference house)



Source: Prepared by the authors.

To carry out the economic analysis, it was necessary to survey the electrical load of the residence, based on Equation (1). This survey involved the identification of the nominal power and the average daily time of use of each household appliance, as shown in Table 1.

Table 1

Equipment used and estimated load consumption

Equipment	Number	Hours of Use/Day (t_i)	Power (W)
Stereo	1	1	150
Water Pump	1	1/4	370
Freezer	1	4	100
Lamp	1	8	20
Lamp	2	8	15
Lamp*	2	8	14
Washing machine	1	0,5	290
Acai Berry Beating Machine	1	0,5	180
Router*	1	24	10
32* TV	1	8	74
Total			1,223
			kWh/day

*Priority loads.

Source: Prepared by the authors.

$$E_{Consumida} = \sum_{i=1}^n P_i \cdot t_i \quad (1)$$

Where:

$E_{Consumed}$ = Represents the total energy consumed per day;

P_i = Power of the equipment;

t_i = Corresponds to the interval of use of a piece of equipment per day (h);

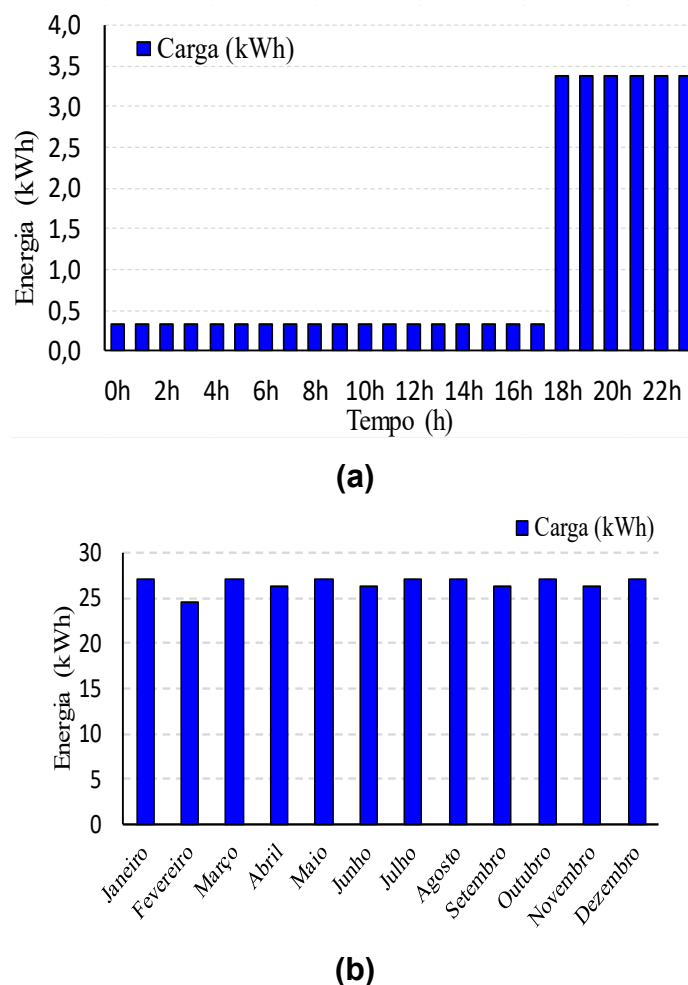
n = Number of equipment;

As shown in Table 1, to fully supply the energy demand of the residence, a *medium-sized off-grid* SFV system would be necessary, consisting of at least four 300 Wp (Watt peak) modules and four 150 Ah (Ampere-hour) batteries. However, the acquisition of a system of this magnitude is not feasible for the villagers, due to factors such as low purchasing power,

the presence of a clandestine electricity grid, albeit unstable, and limited familiarity with photovoltaic solar technology. In view of this scenario, the strategy adopted was the dimensioning of an *off-grid* SFV system aimed exclusively at serving priority loads, making it more accessible and attractive from an economic point of view. According to Table 1, these priority loads correspond to the *internet* router, the television and the lamps. Figure 3 shows the load profile associated with this equipment.

Figure 3

Load of the reference house: (a) daily load, (b) monthly load



Source: Prepared by the authors.

Figure 4 shows the *off-grid* SFV installed in the reference house for load estimation.

Figure 4

Off-grid photovoltaic system installed in the community



Source: Prepared by the authors.

In the economic evaluation that will be shown below, the case studies of the off-grid SFV demonstrated in the previous section are addressed. The analysis includes the exposure of the initial costs, the annual economic balance and the cost of the kWh generated from each system, for the demand conditions.

3 ECONOMIC EVALUATION

3.1 STARTUP COSTS

Table 2 shows the composition and distribution of the costs of the *off-grid SFV components*, as well as the cost associated with the clandestine power grid.

Table 2

Initial Off-Grid SFV Costs

Equipment	Features	Quantity	Value (R\$)
Photovoltaic Module	155 Wp	1	300
Inverter	300 Wp	1	339
Charge Controller	20 A	1	479
Battery	60 Ah	1	430
Total 1,548.00			

Source: Prepared by the authors.

Table 2 shows that the largest expenditure for the implementation of a small *off-grid SFV* corresponds to the acquisition of the charge controller due to the fact that it has technology to search for the maximum power point. However, according to the increase in the system, this initial cost will be for the battery bank.

The generation of electrical power through a single-phase 12.5 kVA (10kW) DG group that provides an output voltage of 127V. Table 3 shows the initial costs associated with this type of electrical power generation.

Table 3

Diesel generator startup costs

Equipment	Features	Quantity	Value (R\$)
Diesel Generator Set	12.5 kVA +motor	1	6.000
Maintenance	annual	3	1.500
Total			7.500,00

Source: Prepared by the authors.

The generation of electricity through the clandestine electric grid had the following initial investment, according to Table 4.

Table 4

Initial costs of the clandestine power grid

Equipment	Characteristic	Quantity	Value (R\$)
Electrical network	By family	1	1.200,00
Total			1.200,00

Source: Prepared by the authors.

3.2 ECONOMIC BALANCE SHEET

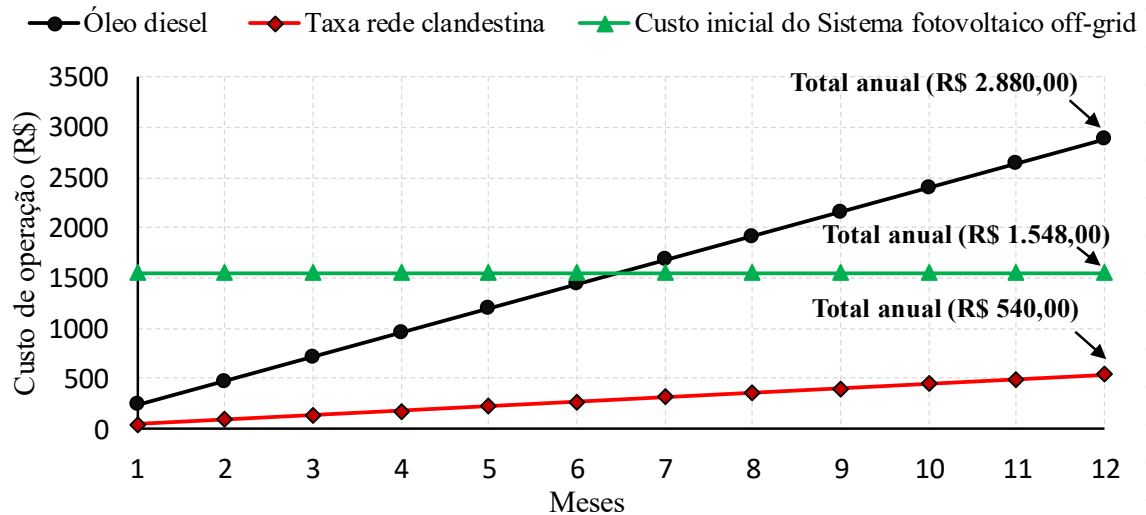
For the economic balance, the following were considered:

Clandestine electricity network - Average rate charged per consumer unit 45.00 R\$/month. The total amount of revenue is used to pay operators who maintain the network, purchase poles, among others (operating expenses).

GD - Cost per liter: 8.00 R\$/Liter. On average, 1 liter of oil is used each day to make up for the lack of the clandestine network (this is a conservative estimate based on ideal operating conditions).

Figure 5

Operating cost curve of energy sources



Source: Prepared by the authors.

3.3 COST OF KWH GENERATED

To determine the cost of the kWh generated for the values of average loads, Equations 2 to 6 were used.

$$CE = \frac{VPLa}{EC} \quad (2)$$

Where:

CE – Cost of electricity (R\$/kWh);

NPV – Annualized net present value (annualized life cycle cost of the system) (R\$);

Ec – Electricity consumed (kWh).

The annualized net present value is determined by the following Equation (3):

$$VPL_A = VPL \times \frac{i \times (1 + i)^n}{(1 + i)^n - 1} \quad (3)$$

i – Minimum attractiveness rate ($a.a$);

n – Analysis period (years);

NPV can be calculated using the following Equation (4):

$$VPL = I + CR_p + \sum_{k=1}^n VP_{(O/M)} \quad (4)$$

Where:

I – Cost of the initial investment (R\$);

CR_p – Replacement cost brought to present value (R\$);

$PV_{(O/M)}$ – Present value associated with the cost of operation and maintenance (R\$).

The term CR_p can be calculated using the following Equation (5):

$$CR_p = \sum_{m=1}^R \left(\frac{CC}{(1+i)^{m \times T}} \right) \quad (5)$$

Where:

R – Number of component replacements during the analysis period;

CC – Component cost (R\$);

T – Useful life of the component (years).

The term $PV_{(O/M)}$ can be calculated using the following Equation (6):

$$VP_{(O/M)} = W \times \frac{(1+i)^n - 1}{i \times (1+i)^n} \quad (6)$$

Where:

W – Sum of total operating and maintenance costs.

4 RESULTS AND DISCUSSIONS

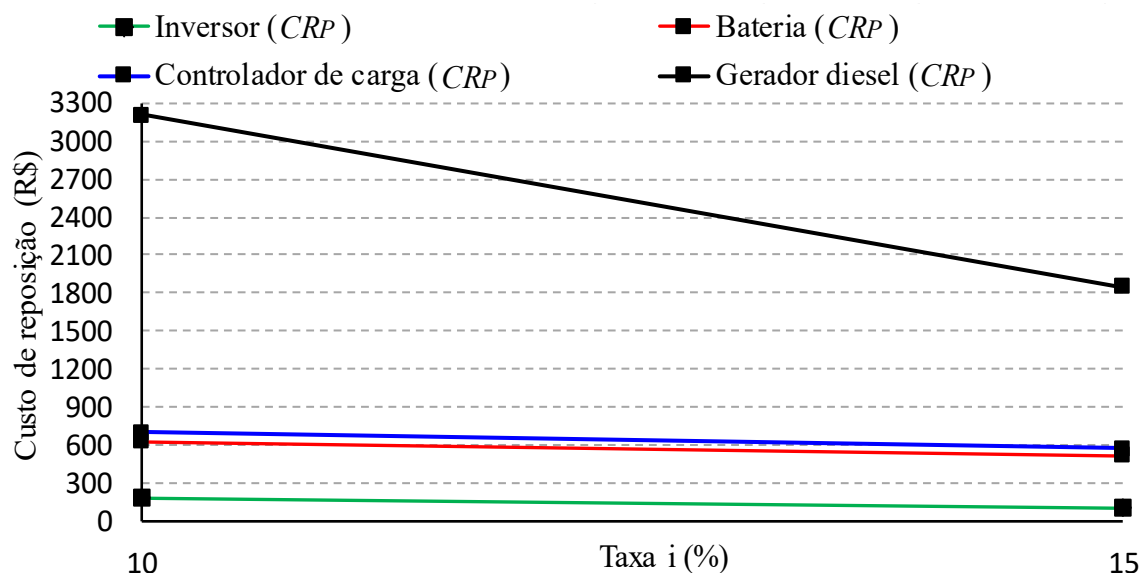
Considering a planning horizon of 20 years, defined based on the useful life of the photovoltaic modules, which represent the component with the longest longevity of the system, minimum attractiveness rates of 10% and 15% were adopted. The annual cost of operation and maintenance of the SFV *off-grid* was estimated at 1% of the initial capital,

totaling R\$ 15.48 per year. The operational useful life of storage batteries is approximately 4 years, which implies four replacements over the period analyzed. For the charge controller, whose average durability is also 4 years, two replacements are planned. The inverter, on the other hand, has a useful life of 10 years, with two replacements estimated during the life cycle of the system. In the case of DG, periodic maintenance costs were estimated at around R\$ 1,500.00 per semester.

Figure 6 shows the replacement costs of the *off-grid SFV components*, as well as those of the diesel generator set. For the inverter, the replacement cost was calculated at R\$ 181.48 with a rate of 10% and R\$ 105.00 with a rate of 15%. The charge controller has estimated values of R\$ 699.00 (10%) and R\$ 571.00 (15%). The battery bank has an estimated replacement cost of R\$ 627.00 with a 10% fee and R\$ 513.00 with a 15% fee. Finally, the diesel generator set has an associated replacement cost of R\$ 3,205.00 (10%) and R\$ 1,850.00 (15%).

Figure 6

Replacement cost of the off-grid SFV components and the diesel generator set



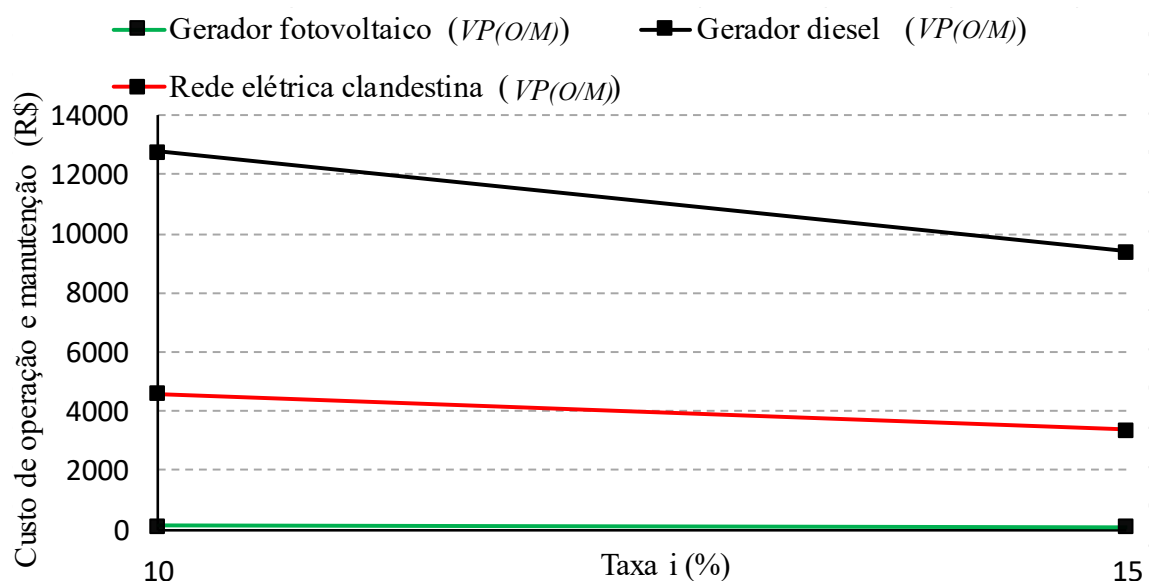
Source: Prepared by the authors.

In the analysis of operation and maintenance costs, the clandestine electricity network was also considered, since the monthly fee charged to each family in the community is intended for the maintenance of the infrastructure, including activities such as tree pruning, cable replacement and general repairs. The total cost associated with the operation and maintenance of this network was estimated at R\$ 4,597.00 for an attractiveness rate of 10%

and R\$ 3,380.00 for 15%. For the off-grid SFV, the corresponding costs were R\$ 132.00 and R\$ 97.00, respectively. DG, on the other hand, had the highest operating costs, totaling R\$ 12,770.00 with a rate of 10% and R\$ 9,389.00 with a rate of 15%. Figure 7 shows the comparison between the operation and maintenance costs of the three energy generation sources analyzed.

Figure 7

Cost of operation and maintenance of electricity generating sources

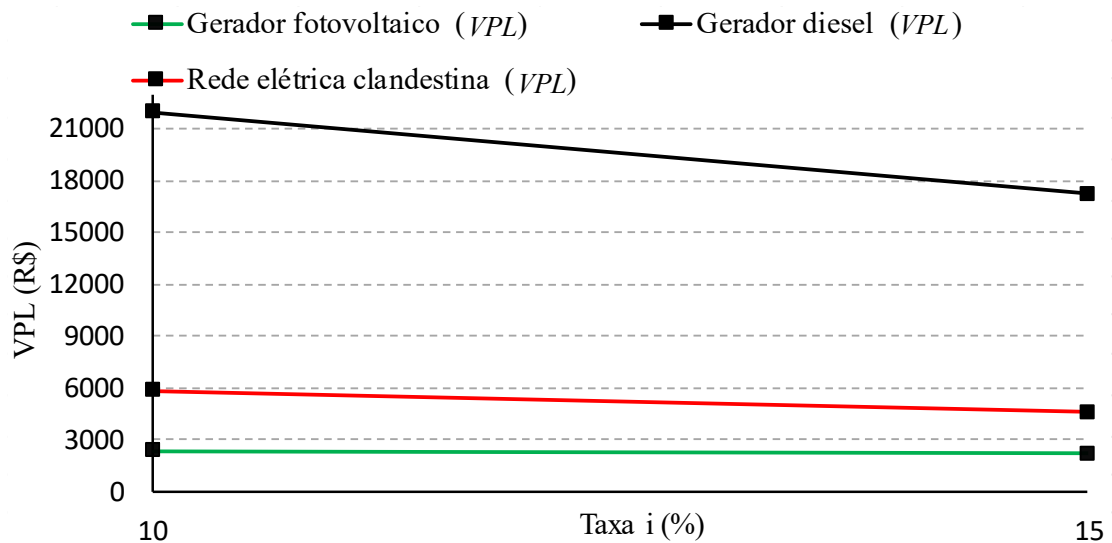


Source: Prepared by the authors.

The *NPV* and *aLPV* of the sources that generate electricity are shown in Figures 8 and 9. The *NPV* of the DG was R\$ 21,975.00 and R\$ 17,239.00, of the SFV *off-grid* was R\$ 2,307.00 and R\$ 2,158.00 and of the clandestine network was R\$ 5,797.00 and R\$ 4,580.00, the rate of 10% and 15% respectively.

Figure 8

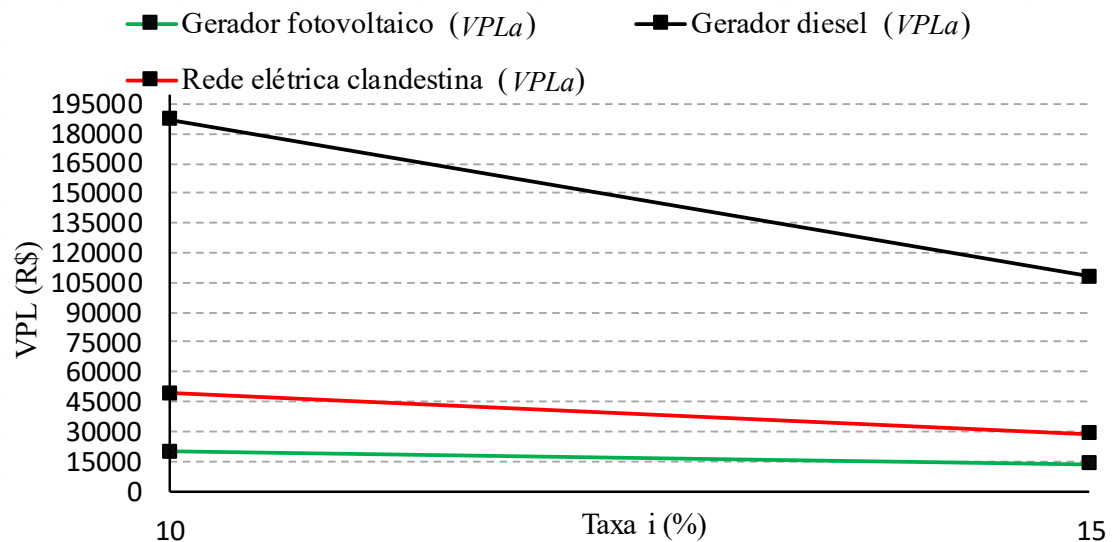
NPV of the electric energy sources



Source: Prepared by the authors.

Figure 9

NPV of the electric energy source

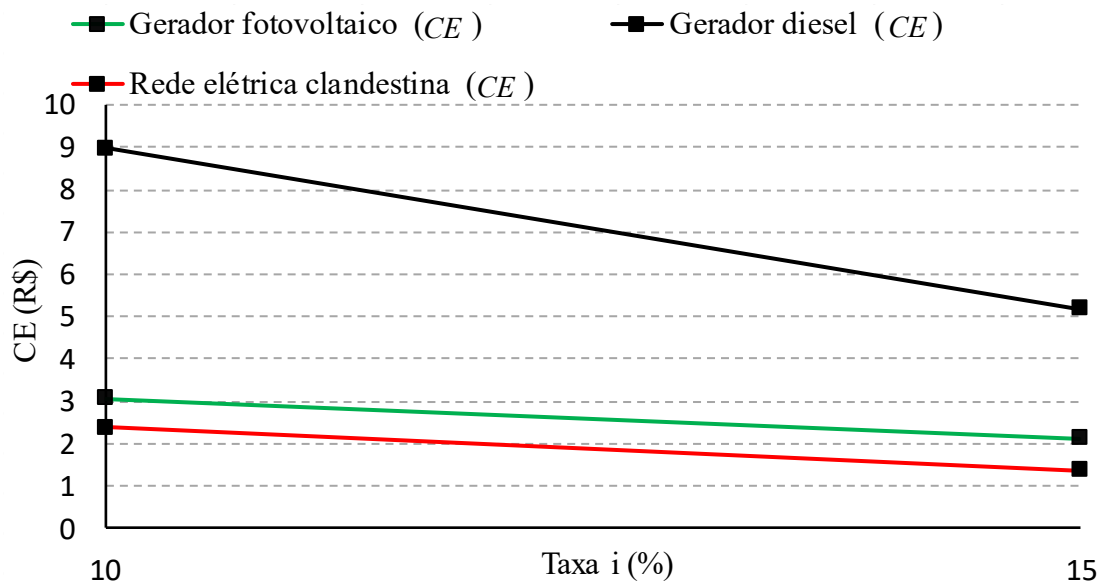


Source: Prepared by the authors.

The cost per kWh of electricity for each generating source is shown in Figure 10. The kWh delivered to the community by the DG was R\$ 9.00/kWh and R\$ 5.20/kWh, the rates of 10% and 15%, respectively. The kWh delivered to the community by the SFV *off-grid* was R\$ 3.10/kWh and R\$ 2.10/kWh and the cost of the kWh supplied by the clandestine network was R\$ 2.40/kWh and R\$ 1.10/kWh at rates of 10% and 15%, respectively.

Figure 10

Cost per kWh of electricity for solar, diesel and hydro sources



Source: Prepared by the authors.

5 CONCLUSIONS

The research presented highlights the importance of adopting *off-grid* photovoltaic systems as a sustainable alternative for the supply of electricity in riverside communities in the Amazon excluded from the National Interconnected System. The economic analysis has shown that while the initial cost of solar systems is higher than that of clandestine grids and diesel generators, their performance over time is more advantageous in terms of cost per kWh, stability in supply, and reduced environmental impacts. Solar energy, in addition to promoting energy autonomy, presents itself as a solution aligned with the needs of low-income populations, contributing significantly to the reduction of energy poverty and the strengthening of sustainable local development. The results obtained reinforce the urgency of public policies that encourage the expansion of clean and decentralized energy solutions, especially in remote areas, strengthening the commitment to an inclusive and just energy transition.

ACKNOWLEDGMENT

The authors would like to thank the Federal University of Pará (UFPA) for its institutional support, laboratory infrastructure, and research incentives, which were fundamental for this study.

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