Energy access, embryonic urbanity, and development in Amazonian villages

Acesso à energia, urbanidade embrionária e desenvolvimento em vilas amazônicas

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ABSTRACT

This paper analyzes the relationship between electrification, sustainable development, and emerging urban structures in small villages of the western Brazilian Amazon. These communities, usually with one to five thousand inhabitants, present an early stage of urban consolidation that depends on reliable infrastructure to sustain wellbeing and socio environmental resilience. Using the concept of embryonic urbanity and the Social Progress Index as analytical references, the study evaluates how electricity access influences education, health, economic activity, and community organization. A case study of Caiambé, in the municipality of Tefé - western Brazilian Amazon, investigates the transition from a diesel-based power plant to a hybrid solar and battery system. Field observations and municipal indicators show that hybridization reduces fuel consumption, increases energy security, and strengthens SDG7 objectives. The results support low carbon strategies for isolated systems and offer guidance for improving the Luz para Todos with decarbonization program.

Keywords: Electrification. Social Progress Index. Hybrid Energy Systems. Amazonian Local Development. Embryonic Urbanity in Amazon.

RESUMO

Este artigo analisa a relação entre eletrificação, desenvolvimento sustentável e formas urbanas emergentes em pequenas vilas da Amazônia brasileira ocidental. Essas comunidades, geralmente com um a cinco mil habitantes, apresentam um estágio inicial de consolidação urbana que depende de infraestrutura confiável para sustentar o bem-estar e a resiliência socioambiental. Utilizando o conceito de urbanidade embrionária e o Índice de Progresso Social como referências analíticas, o estudo avalia como o acesso à eletricidade influencia a educação, a saúde, a atividade econômica e a organização comunitária. Um estudo de caso na vila de Caiambé, no município de Tefé — Amazônia brasileira ocidental — investiga a transição de uma usina a diesel para um sistema híbrido com geração solar e baterias. Observações de campo e indicadores municipais mostram que a hibridização reduz o consumo de combustível, aumenta a segurança energética e fortalece os objetivos do ODS 7. Os resultados apoiam estratégias de baixo carbono para sistemas isolados e oferecem subsídios para o aprimoramento do programa Luz para Todos com diretrizes de descarbonização.

Palavras-chave: *Eletrificação. Índice de Progresso Social. Sistemas Híbridos de Energia. Desenvolvimento Local Amazônico. Urbanidade Embrionária na Amazônia.*

1 INTRODUCTION

Small Amazonian villages play a crucial role in regional territorial organisation, mediating the flow of goods, transportation, and public services between rural areas and municipal centres. These settlements, shaped by indigenous, caboclo, and migrant populations, maintain extractive activities, subsistence agriculture, and mobility along river networks. Despite this importance, they face persistent deficits in education, health care, communication, and energy infrastructure.

Access to electricity is among the most relevant constraints. Many communities depend on isolated diesel-based systems with high operational costs, fuel logistics, and unstable supply. These vulnerabilities affect basic services such as schools, health units, refrigeration, communication networks, and small commerce. Understanding how electrification influences these settlements requires an analytical lens attentive to the slow and uneven process through which small villages begin to express essential urban functions. This condition is captured by the concept of embryonic urbanity.

The Social Progress Index provides a multidimensional framework to evaluate local conditions, but since it operates at the municipal scale, complementary qualitative assessment is required for village level analysis. A gap remains in the literature regarding villages of intermediate scale between micro communities and fully consolidated towns. This work addresses this gap through an examination of Caiambé, a village of two thousand residents that recently shifted from diesel generation to a hybrid system. The aim is to understand how electrification supports local development and contributes to early urban consolidation while advancing SDG7.

2 ANALYTICAL FRAMEWORK

2.1 AMAZON AND THE CONCEPT OF EMBRYONIC URBANITY

The formation of urban environments in the Brazilian Amazon follows trajectories that differ from classical models of urban expansion. The work of Brazilian geographer Milton Santos can provide an essential conceptual basis for understanding these processes. Santos distinguishes the city as a material form from the urban as a set of social relations, flows, and practices that shape the production of space (Santos, 1993, 1997, 2009). In his perspective, urbanity emerges not merely from physical structures but from the organisation of daily life, the circulation of people and goods, the articulation of technical systems, and the political processes through which communities express collective demands. Urban space is therefore produced through social interactions and institutional arrangements that transcend the presence of consolidated infrastructure.

This interpretation is particularly relevant in the Amazon, where many settlements begin to exhibit urban functions before acquiring the physical attributes of consolidated towns. These early expressions of urban life arise through the establishment of schools, health posts, commercial activities, and community associations that structure daily interactions. As Santos's framework suggests, urbanity materialises through social claims and collective practices even in contexts where infrastructure remains incomplete.

Becker's work complements this interpretation by situating Amazonian urbanisation within a long historical process of territorial occupation. Becker describes the Amazon as an urbanised forest, where networks of river circulation, extractive cycles, and migration have shaped the formation of numerous small settlements (Becker, 1990, 1995). According to Becker, these settlements often arise through endogenous dynamics rather than formal planning, resulting in nuclei that combine rural livelihoods with emerging urban structures. This produces an archipelago of small centres that provide basic services, commercial activities, and logistical support across vast riverine territories. Nascimento (2017) reinforces this interpretation by noting that territorial expansion in the Amazon frequently occurs through rapid and unplanned processes that respond to immediate social needs, rather than through long-term planning policies.

In this context, several studies have emphasised the importance of small settlements as nodes of social and economic organisation. Costa *et al.* (2019) highlight the role of these villages in the regional urban hierarchy, functioning as intermediaries between remote communities and municipal centres. Alves Fernandes (2017) in turn, demonstrates how villages like Caiambé develop through successive cycles of extractivism, migration, and infrastructure provision, gradually acquiring a more complex territorial network.

Introducing here, the concept of *embryonic urbanity* emerges from the intersection of these perspectives. It designates a stage in which a settlement begins to develop essential urban functions while maintaining strong rural characteristics and a deep connection to natural resources. The early evolution of urbanity at the local scale emerges from the negotiation of community needs regarding infrastructure. Social claims for housing, transport, sanitation, and, importantly, energy, form the foundation for incremental urban growth and transformation. Just as an embryo requires a constant supply of nutrients to develop into a mature organism, Amazonian villages depend on reliable electricity to support their expansion and the emergence of urban functions. Importantly, this growth can occur in ways that harmonise with the surrounding environment, preserving the life-supporting ecosystems that constitute the forest heritage of these communities. The embracing *Mother Earth* around the young settlement may wither under the weight of resource demands from its embryonic rise, or, in gentle harmony, she may nurture the birth of a city that matures wisely, sustaining her and itself in a shared cycle of lasting growth.

A sustainable model of Amazonian urbanisation should therefore embrace adaptability, integrating modern technological solutions, such as the insertion of renewable energy, into a self-regulating system that aligns with both ecological rhythms and human settlement patterns. In doing so, embryonic urbanity can serve as a framework for promoting local development while respecting and reinforcing the environmental and cultural integrity of the region.

Thus, the metaphor of embryonic urbanity is marked by the progressive consolidation of all other technical systems, including transportation, communication, etc., which enable new forms of social interaction and economic activity. It also appears through the expansion of institutions that regulate community life, such as schools, health units, churches, and small commercial establishments.

Despite these developments, settlements in this stage retain a hybrid nature. Rural practices and forest-based livelihoods remain central to daily life, yet residents increasingly articulate demands for improved services, education, health care, communication, and mobility. These demands exert pressure on public authorities and contribute to the establishment of new infrastructures, reinforcing the transition toward urban functions. As Becker (1995) argues, these processes reflect the dynamic interaction between local populations and broader economic and territorial forces that shape the region.

Through this conceptual lens, embryonic urbanity provides a coherent framework for understanding how small Amazonian settlements evolve and how improvements in electricity supply influence their development trajectories. It highlights the material, social, and symbolic dimensions through which villages transition from rural communities into structured urban environments, shaped by local agency, environmental context, and the gradual establishment of essential infrastructure. This perspective also helps explain how these emerging urban conditions can sustain a rural-urban relationship that supports forest conservation, rather than undermining it.

2.2 ELECTRIFICATION AND LOCAL DEVELOPMENT IN ISOLATED AMAZONIAN SYSTEMS

Energy access is a central driver of social development in the Brazilian Amazon, where many small and medium sized settlements remain outside the National Interconnected System (SIN), as shown in Figure 1. These localities depend on isolated diesel based power plants that form the core of the SISOL program (Brazilian Isolated Sistem Program). The program is governed by the Brazilian Ministry of Mines and Energy and technically coordinated by the Energy Research Company (EPE), which is responsible for planning, auditing, monitoring, and guiding the long-term operation of isolated systems (EPE, 2024, 2025). Across the region, SISOL accounts for more than 700 MW of installed capacity. Although diesel generation ensures supply in remote areas, it is associated with high operational costs, complex logistics for fuel transport, and significant environmental impacts.

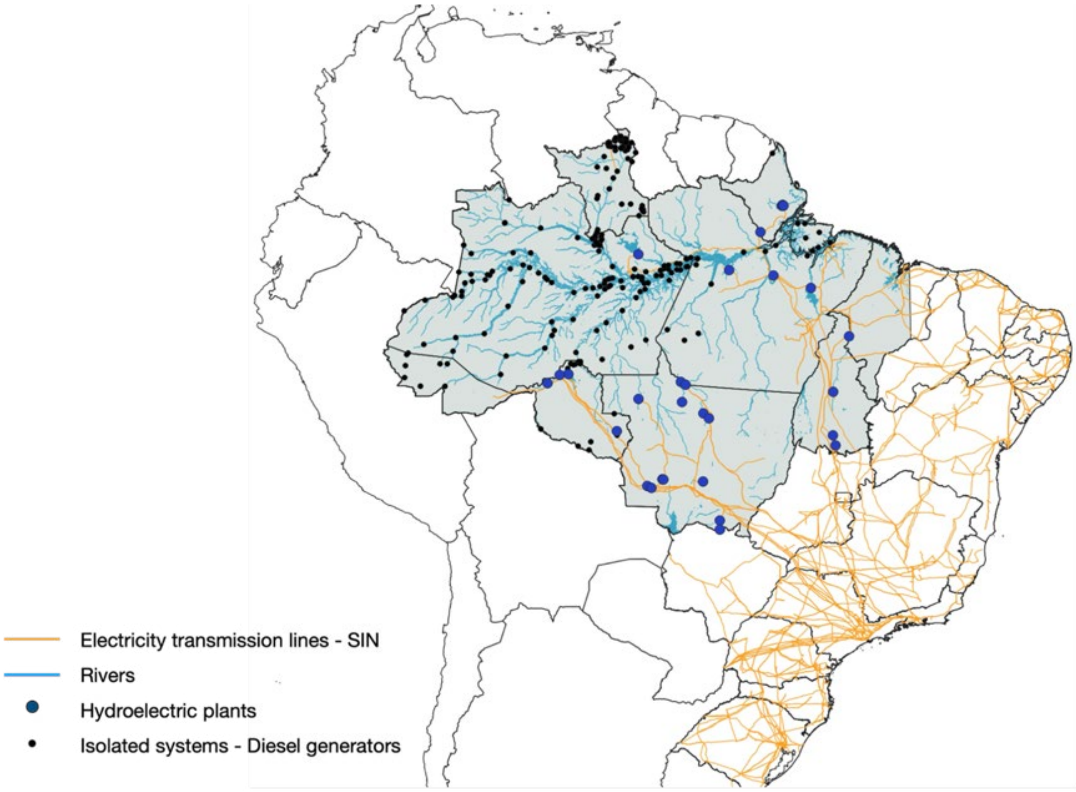

Figure 1 – Electricity infrastructure in the Amazon region

Source: EPE, 2024

The dependence on diesel also affects supply reliability. Seasonal variations in river navigability, transport delays, and fluctuations in international fuel prices expose communities to recurrent risks and unstable costs. These vulnerabilities limit electricity availability for essential public services, including health care, education, water treatment, communication networks, and local commerce, reinforcing structural constraints on development.

A growing body of research highlights the need to adopt cleaner and more resilient solutions. Studies demonstrate the feasibility of renewable sources in remote Amazonian systems (Jean *et al.*, 2021) and point to photovoltaic generation as a strategic option for areas with limited infrastructure (Van Els *et al.*, 2012).Recent assessments emphasise hybrid systems that integrate solar production and battery storage with existing diesel plants (Alves *et al.*, 2023; Soliano Perreira *et al.*, 2024). These configurations reduce fuel use and emissions while improving reliability and stability.

For villages with populations between 1 and 5,000 inhabitants, hybrid systems can offer an intermediate, scalable solution between small off-grid units and the larger systems installed in municipal centres. Their scale aligns with the needs of an emerging urban environment. By reducing dependence on fuel transport and taking advantage of available solar resources, hybrid systems enhance resilience and support the transition toward sustainable energy models.

In this context, electrification can function not only as infrastructure but also as a catalyst for social transformation. Improved energy availability strengthens essential services, fosters economic diversification, and consolidates institutional capacity. These processes contribute to the evolution of villages from dispersed rural clusters into cohesive urban environments, reinforcing the connection between electrification and local development examined in this study.

2.3 THE SOCIAL PROGRESS INDEX AS A REFERENCE FOR LOCAL DEVELOPMENT

The evaluation of development conditions in the Amazon has advanced through the use of multidimensional indicators that capture social and environmental realities beyond economic measures. Among these instruments, the Social Progress Index has become a central reference for assessing regional disparities and monitoring quality of life. Developed by the Social Progress Imperative and adapted for Brazil, the SPI evaluates development through three dimensions: basic human needs, foundations of wellbeing, and opportunity (IPS-Brasil, 2025; Santos *et al.*, 2023; Stern *et al.*, 2021).

Composed exclusively of social and environmental indicators, the SPI provides a comprehensive interpretation of population conditions without relying on income data. This is particularly relevant in the Amazon, where subsistence economies, limited monetisation, and restricted access to services make conventional economic metrics insufficient. The SPI incorporates components such as nutrition, water access, sanitation, housing, safety, education, information access, health outcomes, environmental quality, individual rights, and social inclusion, offering a detailed picture of territorial inequalities.

Municipal scale SPI results reveal persistent deficits in infrastructure and service provision, especially in sanitation, communication, and educational opportunities. In Tefé municipality, which includes Caiambé, several sub indicators highlight structural vulnerabilities in education, communication services, and opportunities, despite comparatively higher performance in housing and basic services. The SPI therefore provides a useful framework for interpreting the conditions under which small villages operate. Figure 2 presents the distribution of the SPI for all municipalities in Brazil. It also highlights the indicator for Tefé, which is the specific focus of this study.

It is important to observe that applying the SPI directly to village-scale analysis presents limitations. Most SPI indicators rely on aggregated municipal data and therefore fail to capture intra-municipal differences. Small villages rarely have systematic data collection or administrative records that would allow precise replication of SPI components. As a result, important aspects of local reality cannot be measured with the same granularity as in municipal evaluations. These constraints require complementary approaches that adapt the SPI structure to local contexts. Qualitative methods, perception-based evaluations, and field observations make it possible to capture local needs and social conditions not reflected in aggregated data. Integrating SPI categories with community perceptions reveals how residents interpret their access to services, evaluate local institutions, and perceive development conditions. This combined approach offers a more coherent interpretation of development at the scale of small villages and supports the investigation of how improved electricity access influences social progress in places with limited administrative data.

In this sense, the SPI serves both as a conceptual guideline and a comparative reference. It anchors the analysis in a robust multidimensional framework while enabling the examination of local dynamics that remain invisible in formal statistics. This dual approach is essential for understanding development processes in Amazonian villages, where local realities differ significantly from municipal averages and where the impacts of electrification are most strongly perceived in daily community life.

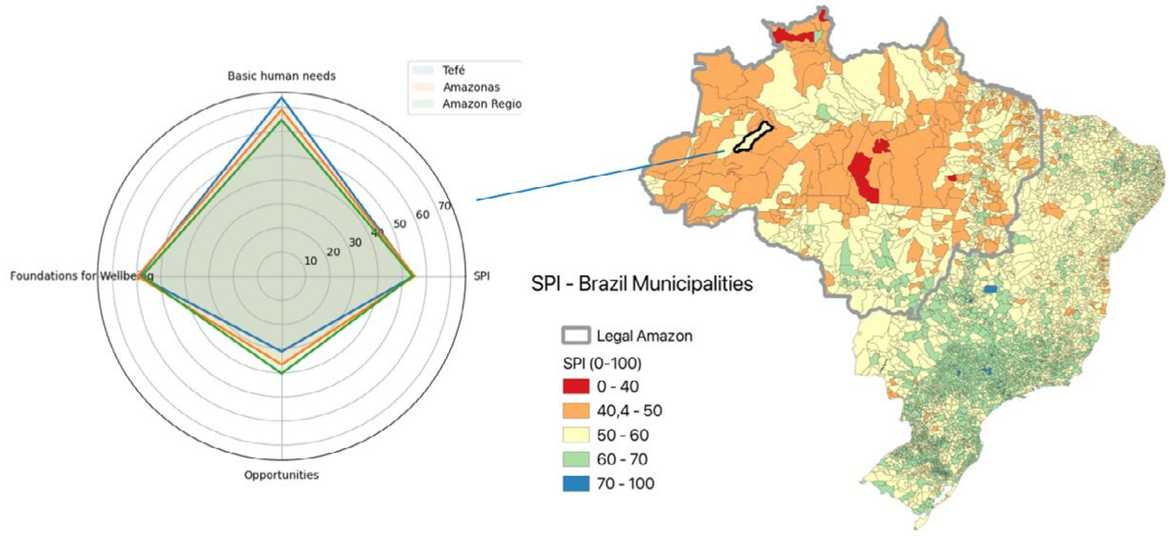

Figure 2 – Social progress index and sub-Indicators for Tefé municipality

Source: IPS-Brasil, 2025

2.4 ELECTRIFICATION AND SOCIAL INDICATORS IN THE BRAZILIAN AMAZON

The regional landscape of electrification in the Brazilian Amazon reveals a persistent pattern of spatial inequality that directly affects the living conditions of local populations. A clear illustration of this context is provided in Figure 1, where the electricity infrastructure in the Amazon region is illustrated. The map shows the extensive distribution of isolated power systems across the western region, highlighting the concentration of diesel-based generation units that supply towns and villages disconnected from the National Interconnected System. This spatial configuration underscores the structural dependence of the region on isolated systems and the challenges of guaranteeing electricity access in vast and sparsely populated territories.

Regional disparities become even more evident when household electricity access is compared across all Brazilian municipalities. Figure 3 presents the percentage of electrified households, revealing lower coverage levels in most of the Amazonian municipalities relative to national averages. These differences reflect the logistical and infrastructural constraints of extending distribution networks across remote riverine areas. They also align with the broader deficits in sanitation, water treatment, solid waste management, and communication services captured by the 2022 Census (IBGE, 2023), as shown in Table 1.

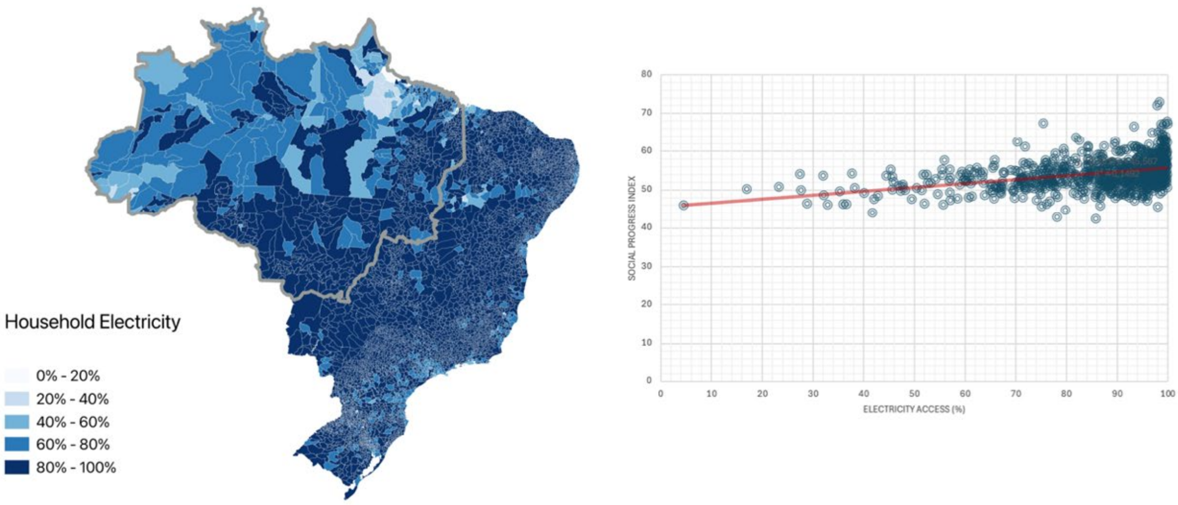

Figure 3 – Electricity access in households for the Amazon region

Source: IPS-Brasil, 2024

Table 1 – Indicators of Household Infrastructure Access.

State of the Amazon region	*Sanitary Sewer Collection (%)*	*Potable water treatment (%)*	*Solid waste management (%)*	*Electricity access (%)*
Acre	36.7	52.6	78.4	75.1
Amapá	12.1	43.4	90.8	70.8
Amazonas	33.4	66.1	82.8	65.4
Maranhão	18.1	66.2	71.4	94.8
Mato Grosso	34.0	80.7	88.7	82.34
Pará	20.0	48.9	78.1	83.2
Rondônia	13.6	48.2	79.5	71.5
Roraima	45.0	81.3	80.4	80.7
Tocantins	29.6	81.7	85.2	85.3
Brazil	64.7	83.9	91.7	87.0

Source: IBGE, 2023 and EPE, 2024

Understanding how these infrastructural conditions relate to social development requires a multidimensional analytical perspective. The Social Progress Index provides such a framework. In Figure 3, the relationship between the SPI and electrification in all Amazonian municipalities is presented. A clear relation can be observed, which also reflects the maps of Figures 2 and 3. This reinforces the interpretation that territorial inequalities in infrastructure influence social outcomes.

A more direct relationship between electrification and social indicators is presented through statistical analysis of the SPI sub-indicators, which is presented in Figure 4. Their relationship with electricity access shows strong linear correlations between the percentage of electrified households and the three SPI dimensions. These relationships are quantified in Table 2, which reports coefficients of determination R2 above 0.95 for all dimensions.

The strongest correlation is observed for the Basic Human Needs dimension, consistent with the central role of electricity in enabling water treatment, sanitation, food preservation, and essential services such as lighting and health care. The Opportunity dimension also increases with electricity access, although with a slightly lower coefficient, reflecting the fact that improvements in education, income generation, and mobility depend on a wider set of institutional and economic factors.

Table 2 – Statistical Correlation parameters for SPI sub-indicators and electricity access in Amazon municipalities.

Correlation parameter	*Basic human needs*	*Foundation of Well-being*	*Opportunity*
Coefficient	0.75	0.66	0.47
R-Squared	0.972	0.964	0.959
t-statistic	151.3	133.2	124.2
p-value	< 0.001	< 0.001	< 0.001
Qualitative interpretation	Strongest effect	Strong effect	Still strong, but relatively lower

Source: IPS-Brasil, 2024

Together, these maps and figures demonstrate three central points:

I. The Amazon remains strongly dependent on isolated diesel-based systems, with substantial territorial inequalities in electricity infrastructure (Figure 1).

II. Electricity access varies significantly between Amazonian states, reinforcing patterns of socio-spatial vulnerability (Figure 3 and Table 1).

III. Electricity access is strongly associated with social progress, indicating that improvements in electrification can influence multiple dimensions of municipal development (Figures 3 and 4; Table 2).

Within this regional context, the case study dedicated to a typical village becomes particularly relevant. As part of the isolated systems program and located in one of the states with the lowest electrification coverage, the present study case can allows relevant reflexions in the reseach objectives.

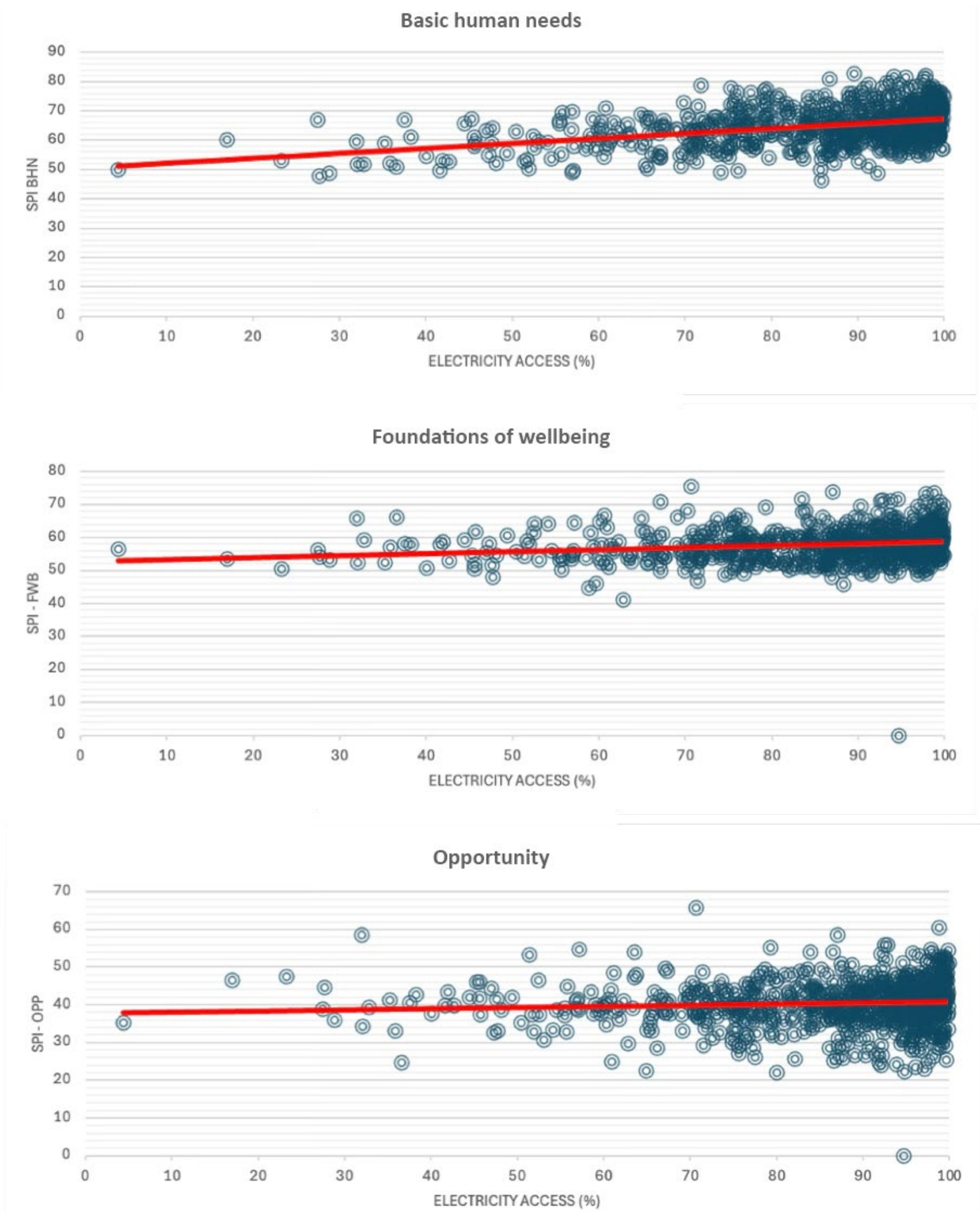

Figure 4 – SPI sub-indicators and their relationship with electricity access in Amazon municipalities

Source: IPS-Brasil, 2024

3 MATERIALS AND METHODS

3.1 SELECTION OF THE STUDY CASE VILLAGE

The selection of Caiambé as the case study follows conceptual, territorial, and technical criteria that reflect the objectives of this research. The study aims to examine how electrification supports local development in small Amazonian villages that exhibit early stages of urban consolidation. In this context, Caiambé represents an appropriate empirical setting due to its demographic scale, economic profile, institutional relevance, and recent changes in its electricity supply (Alves-Fernandes, 2017). Caiambé is located approximately 38 km downstream from the town of Tefé, along the Solimões River, in the western Brazilian Amazon (see Figure 5). The village hosts around 2,000 residents, most of whom live in a compact urban centre where schools, health posts, retail shops, and community institutions are located. The remaining population is dispersed across surrounding rural areas and lake margins with strong ties to fishing and smallholder agriculture.

Figure 5 – Caiambé village: aerial village and location maps

Caiambé was selected for three main reasons. First, it is part of the National Program for Isolated Systems, making it representative of small Amazonian villages that depend on diesel-based power plants. Caiambé is supplied by a diesel power plant with a contracted capacity of about 1.4 MW (EPE, 2025), established to meet the projected growth of electricity demand through 2034. The system currently operates with a lower load because the installed capacity is greater than present consumption, allowing the village to absorb future demand increases without new investments.

Second, the village reflects an embryonic urban condition, in which small settlements gradually organise demands for education, health care, communication, and sanitation. Its social and economic structure reveals the slow consolidation of urban functions while maintaining strong ecological and cultural ties to the surrounding forest. In this study, the interpretation of this embryonic stage considers both the conditions described by Alves-Fernandes (2017) and the recent advances in local infrastructure reported by households during fieldwork. These perceptions highlight changes in public services, mobility, and community organisation, as well as political and social claims made by residents over the last decade. This combination of past and current evidence makes Caiambé an appropriate case for analysing how electrification interacts with local demands and shapes the configuration of its emerging settlement space.

Third, the village recently experienced a significant change in its electricity supply. In 2025, a solar array of 300 kW was installed to complement the diesel plant, with the goals of reducing fuel use, improving supply reliability, and lowering emissions. This transition offers direct evidence to discuss the adoption of cleaner and more resilient energy systems in isolated Amazonian contexts.

The research team carried out three field missions to Tefé and Caiambé between 2024 and 2025. These included direct observation, meetings with local leaders, interviews with residents, and technical visits to both the diesel plant and the new solar installation. Additional information was gathered from official statistics, municipal documents, and the EPE Isolated Systems Dashboard. The study by Alves-Fernandes (2017) also provides essential historical and socio-economic insights into the village.

3.2 COMPARATIVE METHODOLOGY FOR ASSESSING SOCIAL PROGRESS (CAPSP)

The evaluation of development conditions in Caiambé requires a methodological approach that captures the specific realities of small Amazonian villages, where municipal statistics do not reflect the daily experiences of residents. To address this limitation, a comparative and perception-based method was created, combining elements of the Social Progress Index with field observation, informal interviews, and participatory assessment.

Municipal SPI results for Tefé provide a useful reference but cannot be directly applied to Caiambé, since systematic data are not collected at the village scale. The Comparative Assessment of Perceived Social Progress was therefore developed to incorporate residents' perceptions and their comparative understanding of local conditions.

The method adopts the main SPI dimensions, adjusted to the village context: health, education, basic infrastructure, security, communication, environmental quality, and social life. Each domain is evaluated through locally relevant aspects, such as access to primary health care, availability of medicines, quality of electricity and water services, waste management, and mobility.

Residents are invited to compare Caiambé with a reference locality, usually Tefé, which they know well through frequent social and economic interactions. This comparative exercise strengthens the reliability of responses. A simple question guides the evaluation of each dimension:

"How do you evaluate this aspect of life in Caiambé compared to the reference locality (Tefé city)?"

Responses use a five-point scale from "much better here" to "much worse here," or a numerical scale from minus two to plus two to facilitate analytical correction of the SPI. Open questions allow participants to expand on their views and highlight issues not captured by structured categories, adding cultural and contextual depth to the evaluation. This method combines formal indicators with local knowledge to produce a more accurate understanding of social progress in small communities.

A complementary assessment was conducted through interviews with local specialists, business owners, government staff, and researchers familiar with Tefé. They compared economic activities in Caiambé with those of the municipality, identifying productive chains, market access, employment conditions, and the main challenges for economic development.

After assessing the Social Progress Index using the CAPSP approach, perceptions collected from households and other local actors were organised to support the development of a SWOT matrix. This step allowed the identification of strengths, weaknesses, opportunities, and threats related to the village's social conditions and the evolution of its local infrastructure. The reanalysis of the qualitative and quantitative perceptions provided by residents made it possible to consolidate a synthetic view of the community position, highlighting elements that influence the interaction between electrification and local development.

3.3 ENERGY SYSTEM ANALYSIS AND LOCAL DEVELOPMENT INDICATORS

The third part of the methodology examines the electricity supply in Caiambé and its relation to local development. This analysis combines technical data from the isolated diesel system, information from the new solar installation, and development indicators adapted to the village scale. The objective is also to understand how changes in electricity supply support social wellbeing, economic activities, and environmental conditions.

Two main sources inform the technical characterisation. The first is the EPE Isolated Systems Dashboard (EPE, 2025), which provides official data on installed capacity, annual energy production, fuel consumption, and projected demand. The second source is field observation at the diesel power plant during research missions, which made it possible to examine operational practices, load patterns, and the condition of the distribution network.

The analysis begins with annual and monthly generation data, including diesel consumption and generator efficiency. These variables help estimate the environmental burden of diesel use and the extent to which electricity consumption reflects the early urban development of the village.

The next step evaluates the impact of the solar system installed in 2025, composed of a 300 kW array and battery storage for short term energy support, and its possible expansion for a larger configuration. The hybrid energy systems evaluated in this study were simulated using the *Coralina platform®* for hybrid systems developed at the University of Brasilia (Brasil Junior *et al.*, 2021). The platform computes the annual operating behaviour of each configuration, including hourly electricity production, fuel consumption, and battery operation. It also calculates the Levelized Cost of Energy by applying standard procedures based on capital expenditures and operational expenditures. These cost parameters follow the reference values and methodological recommendations published by Irena (2025), adapted to the Amazonian reality, which provide consistent benchmarks for investment, maintenance, and replacement costs for isolated and hybrid power systems.

A qualitative assessment of electricity demand complements the technical analysis. Observations of household appliances, productive activities, public services, and community facilities reveal typical energy uses and the potential for demand growth. This is important because early urban development often brings rapid changes in consumption related to claims for better services, improved communication, refrigeration, water pumping, and education.

Energy data are then integrated with local development indicators through a qualitative and interpretive approach. Technical findings are compared with results from the CAPSP approach to determine whether improvements in electricity supply match residents' expectations and daily experiences. This step highlights the role of electricity as an enabling factor for development and shows how better supply reliability, lower costs, and reduced environmental impacts can support social gains and economic diversification.

4 RESULTS AND DISCUSSIONS

4.1 LOCAL SOCIAL PROGRESS INDICATORS

As established in the CAPSP methodology, the starting point for constructing indicators for the district is based on the values corresponding to the municipality of Tefé. These indicators are obtained from governmental databases, following the procedure defined by Imazon (IPS-Brasil, 2025). Figure 6 presents an overview of these indicators, consolidated into the sub-indicators that make up the index, upon which an adjustment is proposed for the development of Caiambé-specific indicators.

Figure 7 shows the correction applied to the village of Caiambé. This correction consists of a qualitative consolidation of the indicators presented in Figure 6, with adjustments ranging from –2 to 2, as established in the methodology described in item 3.2. Following the CAPSP approach, the estimated SPI score for Caiambé village is 49.2.

The rationale for the corrections applied to each indicator is discussed below, based on observations gathered during field assessments.

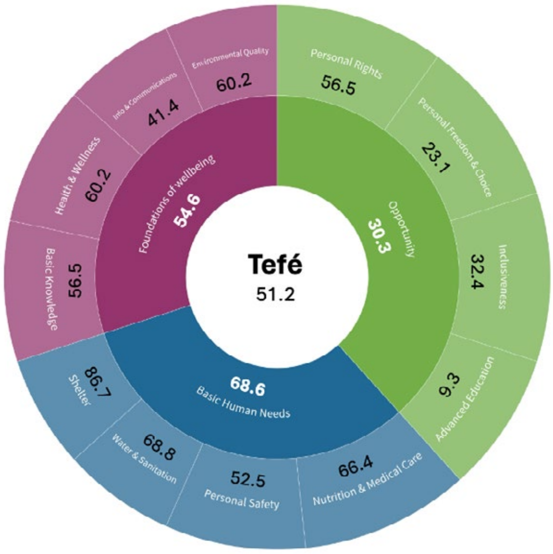

Figure 6 – Social progress index indicators for Tefé municipality

Source: IPS-Brasil, 2024

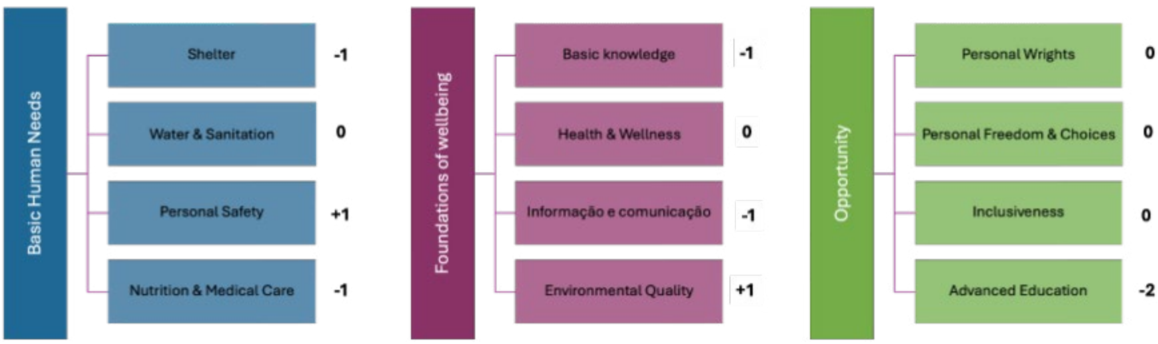

Figure 7 – Corrections between -2 and +2 of the SPI indicators using CAPSP

Source: IPS-Brasil, 2024

a) Basic Human Needs

The sub-indicators for Caiambé are quite similar to those of Tefé. However, the fact that Caiambé is a small settlement of approximately 2,000 inhabitants—compared with a municipality of 65,000—results in a slight relative advantage in some fundamental conditions for quality of life.

- Nutrition and medical care: Although the village has vaccination coverage and basic healthcare services, infant mortality and malnutrition indicators still weigh down overall performance. This reflects persistent inequalities in access to, and quality of, essential healthcare. Nonetheless, no major differences in food security or basic medical attention are observed when compared to Tefé. In more complex cases, residents typically rely on river transport to access health infrastructure in the municipal centre.

- Water and sanitation: The village has made progress in potable water supply in its urban core, complemented by private wells. Wastewater disposal for most of the population relies on septic tanks. Significant issues remain, including high distribution losses and incomplete service coverage, directly affecting public health. Investments are needed to establish a basic sewage network in the central area and to provide technical guidance for community-based sanitation alternatives adapted to local conditions. Solid waste management is a critical concern requiring public intervention. Even so, the situation is not substantially different from that of the municipal seat.

- Housing: Housing conditions are reasonable for an Amazonian village, with good electricity coverage and acceptable structural quality (walls, flooring). This suggests relatively organised urban development. However, many precarious dwellings persist. Given the village's small scale, housing tends to be slightly more accessible for most residents when compared with Tefé.

- Safety: In Tefé, this is the worst-performing sub-indicator, with high homicide rates (particularly affecting youth and women) and traffic accidents severely undermining well-being. Violence poses a real threat to social progress in the municipality. By contrast, Caiambé exhibits a much more peaceful environment, characteristic of small Amazonian settlements.

b) Foundations of Well-Being

This dimension reveals serious limitations—especially regarding education and access to information—although in many aspects Caiambé resembles the municipal indicators.

- Basic education: High dropout rates, age–grade mismatch, and grade repetition reflect structural weaknesses in the educational system and persistent barriers to student retention. Conditions are slightly worse than in Tefé.

- Information & communication: One of the weakest points. Fixed and mobile internet coverage remains limited and of poor quality, undermining access to information, remote learning, and digital inclusion.

- Health: Life expectancy is reasonable, though chronic tropical diseases contribute to avoidable mortality. Rising obesity rates signal an ongoing epidemiological transition.

- Environmental quality: Caiambé presents a moderate environmental quality index, performing better than Tefé. This reflects local environmental diversity, with intact forest areas and high lake water quality. Few pressures—such as deforestation, fires, or acute climate vulnerability—are observed.

c) Opportunity

This is a critical dimension—both for Caiambé and for Tefé—showing very low overall performance, revealing the lack of enabling conditions for residents to fully develop their potential.

- Individual rights: Some institutional structures exist for social programs and judicial access, but procedural overload remains a persistent challenge.

- Personal freedoms and choice: Very low. Early pregnancy, limited access to cultural and recreational activities, absence of parks, and the incidence of child labour constitute serious obstacles for youth development. There are, however, some positive points associated with community cohesion.

- Inclusive society: Gender, ethnic, and racial inequalities are evident. Political representation is also low, including movements advocating for the creation of an independent municipality.

- Advanced education: This is the worst-performing indicator. The share of the workforce with higher education is very small, ENEM performance (Brazilian access test for university education) is insufficient, and women are underrepresented in tertiary education. This severely constrains the municipality's capacity to innovate and generate new opportunities. The indicator is significantly lower than in Tefé, which hosts an advanced campus of the Amazonas State University. Although the local secondary school has been making efforts to improve high-school outcomes, substantial additional work is required to achieve reasonable levels of access to higher education in the village.

To complement and systematise the evaluation derived from the Social Progress Index (SPI) adjustments, a SWOT analysis was developed for Caiambé. The SWOT diagram in Figure 8 synthesises the qualitative corrections applied to the SPI indicators, offering an integrated perspective on the village's social progress, vulnerabilities, and potential pathways for improvement.

a) Strengths

Caiambé exhibits several positive attributes that support local well-being. The village benefits from a relatively peaceful social environment, with significantly lower levels of violence than the municipal centre. Basic housing conditions—such as electrical coverage and essential structural adequacy—are reasonably established, contributing to stability in everyday life. Environmental conditions also represent a strong point: intact forest areas, good lake water quality, and limited pressures from deforestation or fire events reinforce local ecological resilience. The presence of basic healthcare and vaccination services, even if limited in complexity, further contributes to foundational well-being.

b) Weaknesses

Despite these strengths, structural weaknesses remain substantial, particularly in access to quality education, information, and communication. High school dropout rates, age–grade mismatch, and weak performance in secondary education limit long-term opportunities. Internet access—both mobile and fixed—remains insufficient for modern information needs, restricting digital inclusion. Water and sanitation infrastructure is incomplete, with distribution losses, reliance on septic tanks, and inadequate solid waste management affecting public health. The scarcity of advanced educational opportunities and the very low proportion of residents with higher education constitute critical limitations for human capital development.

c) Opportunities

Caiambé has important opportunities for advancing social progress. Its small scale and cohesive community structure facilitate targeted improvements, such as community-based sanitation, local water system optimisation, and expanded digital infrastructure. The proximity to the municipal seat, although requiring river transport, allows for integration into broader health, education, and administrative services. Emerging regional initiatives for rural electrification, connectivity, and environmental conservation may also benefit the village. Moreover, the growing demand for sustainable development models in the Amazon positions Caiambé as a potential pilot site for innovative community-centred interventions.

d)Threats

The village faces several external threats that may compromise future progress. Demographic pressures, economic stagnation, and limited institutional capacity can exacerbate inequalities and restrict long-term development. Climate-related risks, such as alterations in river levels, extreme rainfall, or prolonged droughts, pose direct challenges to water supply, mobility, and local livelihoods. Persistent socio-economic vulnerabilities, such as early pregnancy and child labour, hinder youth development and perpetuate cycles of disadvantage. In addition, the absence of higher education opportunities and skilled employment may accelerate outward migration, reducing local human capital.

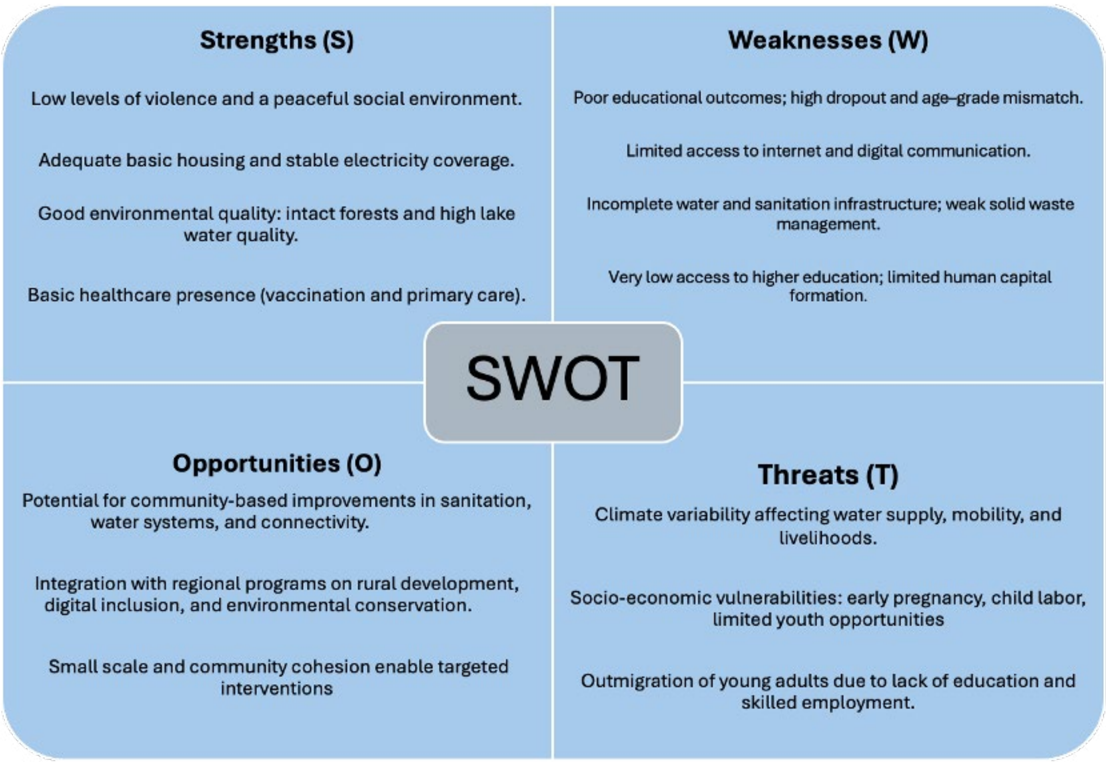

Figure 8 – SWOT diagram for SPI evaluation of Caiambé village.

Source: The authors

In summary, the observed social conditions in Caiambé reveal a community with significant strengths—such as a peaceful environment, affordable basic housing, and favourable environmental quality—yet remains constrained by structural weaknesses in education, sanitation, and access to information. While opportunities exist for targeted interventions and integration with broader regional development initiatives, persistent vulnerabilities and external pressures continue to limit social progress.

These constraints are further compounded by the village's dependence on a fragile and costly energy infrastructure. At present, all local electricity demand is supplied exclusively by diesel generators, a condition that not only restricts economic opportunities and service quality but also increases operational costs and exposure to fuel logistics. This context underscores the need to evaluate alternative energy pathways capable of supporting improved social outcomes while reducing dependence on diesel-based systems.

4.2 ELECTRICITY SUPPLY AND LOCAL SOCIAL PROGRESS

The electrification of Caiambé began in 1986 through an initiative of the state government with Amazonas Energy Company, which implemented a rudimentary and intermittent electricity supply based on small diesel generator sets (Alves-Fernandes, 2017). This situation reflected the pattern commonly observed in many settlements of the Amazon region, where technical limitations, high operational costs, and logistical constraints often restricted the reliability of local energy systems. Over time, the extension of electricity to households and to the main social facilities of the village expanded gradually, driven by the persistent claims of residents. This process illustrates the dynamics of embryonic urbanity, in which access to electricity emerges as both a symbol and a driver of community consolidation and local development. According to Alves-Fernandes (2017), only 27% of the registered consumers in Caiambé were served in 2014. This precarious condition changed significantly after the implementation of the *Luz para Todos* program in 2018, when the local grid was formalised and progressively expanded. The continuous enlargement of the distribution network, which its expasion is visible in Figure 9, reflects the growing urban demands of the village and its transition toward a more structured local infrastructure.

By 2024, the electricity supply in Caiambé was fully dependent on isolated diesel generator sets with a contracted capacity of 1.4 megawatts, operating continuously to meet local demand under conditions typical of remote riverine communities of the Amazon. Despite the operational and environmental challenges of this model, its stability has supported essential services and enabled modest economic growth in the village. Current projections indicate a persistent increase in electricity demand for the coming decade, associated with demographic expansion, improvements in public services, and the strengthening of local commerce and productive activities. Table 3 presents the main characteristics of the electricity supply in Caiambé, illustrating the relevance of energy access as a foundational element (or a consequence) of local social progress.

Table 3 – Electricity facilities numbers in Caiambé in 2024

Contracted power	1,408 MW
Local demand	642 kW
Diesel Consumption	915,296 liters/y
Emissions	2,512 tCO2e
Cost of energy	0.50 USD/kWh
Annual generation	2,297 MWh

Source: EPE, 2025

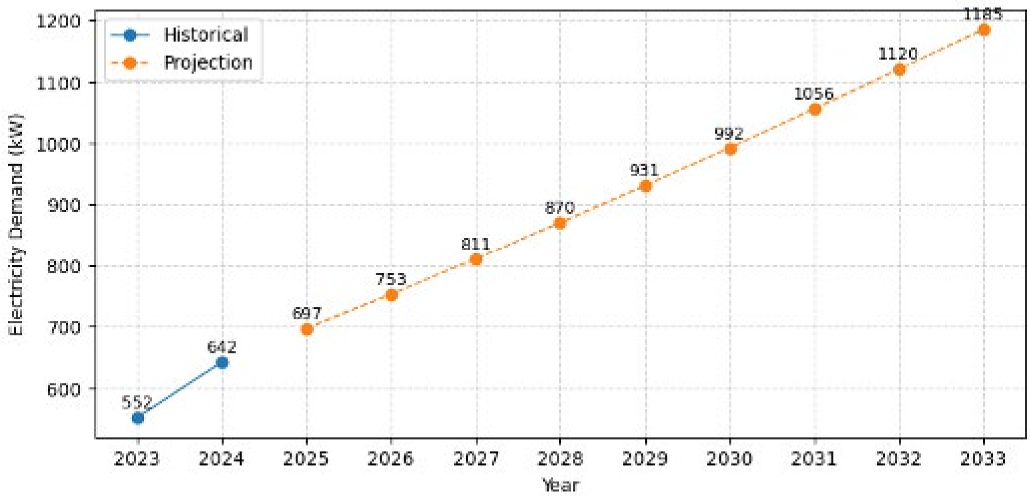

Figure 9 – Local electricity planned demand of Caiambé

Source: EPE, 2025

As illustrated in Figure 10, Caiambé exhibits a daily electricity load profile characteristic of small Amazonian villages, with residential consumption as the dominant component. The evening peak occurs around 9 pm, driven mainly by the simultaneous use of lighting, refrigeration, ventilation, and small household appliances. The hourly curves for 2024, including their annual variability and the parameterisation of the Duck Curve model (Pitra; Mu, 2021, for instance), were obtained from the EPE database. These curves provide a detailed understanding of local consumption behaviour and support the design of strategies to incorporate renewable energy sources through photovoltaic generation and battery storage.

The absence of industrial activity and large commercial consumers results in a relatively low average demand over the day, combined with marked fluctuations in instantaneous power requirements. This dynamic produces recurrent operational mismatches between the rated capacity of the diesel generators and the actual load. As a consequence, during extended off-peak periods, the generators operate at loads well below their optimal efficiency range, increasing fuel consumption per unit of energy delivered, accelerating equipment wear, and raising overall operational costs. This condition underscores the relevance of hybrid energy solutions that can smooth load variability, reduce diesel dependence, and enhance the sustainability of the local electricity supply.

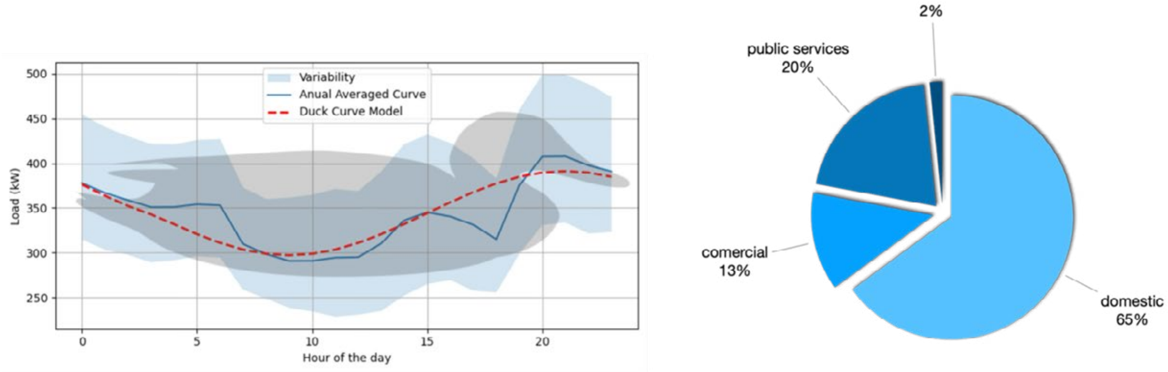

Figure 10 – Electricity Load profile in Caiambé

Source: EPE-Dashboard, 2025

After June 2025, the commissioning of a hybrid energy system composed of a solar power plant and a battery storage unit was initiated. In this first phase, only the 300 kW photovoltaic system entered into operation. Figure 11 presents the annual average behaviour of daily operations for two configurations: the installed 300 kW solar plant and a planned 1000 kW system combined with a 500 kWh lithium-ion battery bank. The simulations were performed using a typical meteorological year for solar irradiation and temperature conditions provided by the World Bank-Esmap (2025). The solar power plant model incorporates performance variations associated with local temperature and irradiation, as well as detailed estimates of losses across all system components.

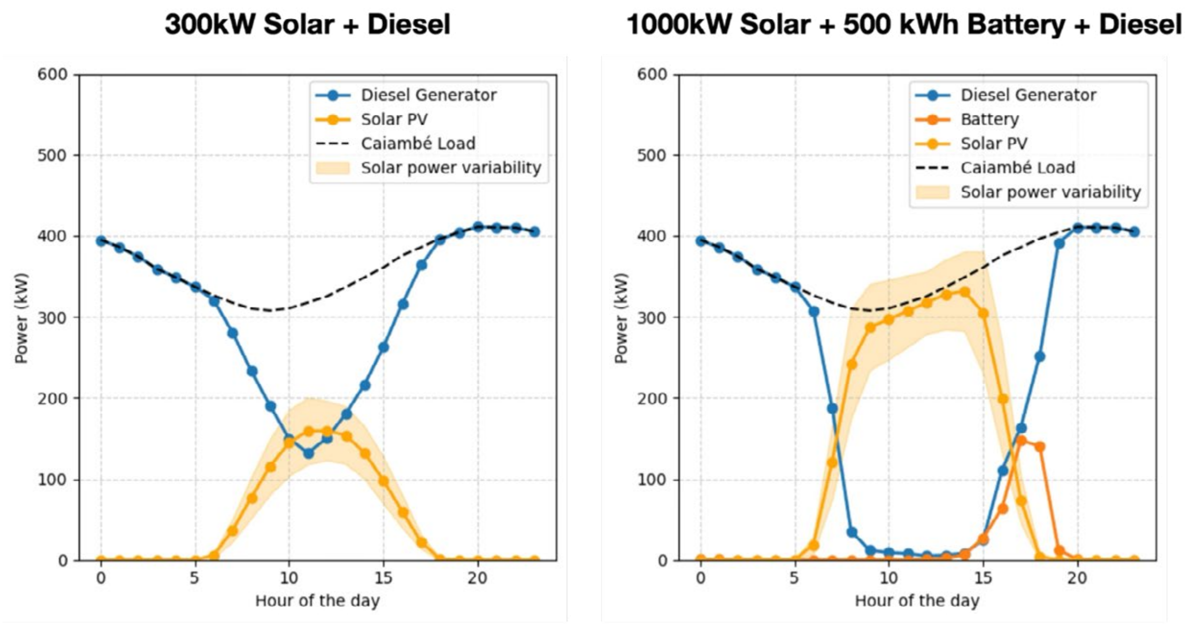

Figure 11 – Averaged Daily operation of the hybrid energy systems for Caiambé village - Modelled using Coralina Platform

Source: Brasil Junior, 2021

Table 4 – Annual operation of hybrid energy systems for Caiambé village (Simulations from Coralina platform)

Configurations	500 kW Diesel generators units 300 kW Solar PV	500 kW Diesel generators units 1000 kW Solar PV 500 kWh Li-ion batteries
Diesel Consumption	795,9 liters/y	571,3 liters/y
Emissions	2,133 tCO2e	1,531 tCO2e
Cost of energy	0.39 USD/kWh	0,33 USD/kWh

Source: The authors

The simulation results for the hybrid system show a marked improvement in operational performance. For the solar 300 kW configuration, all energy produced by the solar plant is fully absorbed by the village load during daylight hours. This direct coupling between solar generation and consumption naturally reduces fuel use, since the diesel generator operates at a lower output during periods of strong solar irradiation. A much more substantial reduction in fuel consumption is observed with the proposed 1000 kW solar plant combined with a 500 kWh battery bank. In this configuration, diesel generation is significantly displaced, as illustrated in Figure 11. The battery bank supplies part of the demand during the evening peak, smoothing the load and further decreasing the reliance on the generators.

The current diesel-based system in Caiambé requires 915,296 litres/year of fuel and emits 2,512 tCO2e/year, with an energy cost of 0.50 USD/kWh. The introduction of a 300 kW solar plant reduces diesel consumption to 795,900 litres/year, a decrease of 13%, while emissions fall to 2,133 tCO2e/year, a reduction of 15%. The cost of electricity drops to 0.39 USD/kWh, showing that even modest solar penetration provides immediate economic and environmental gains.

The full hybrid configuration with 1,000 kW of solar PV and a 500 kWh battery bank offers a much deeper transformation of the local energy mix. Diesel consumption decreases to 571,300 litres/year, a reduction of 38% compared to the diesel-only system. Emissions fall to 1,531 tCO_2e/year, representing a 39% reduction. The energy cost decreases to 0.33 USD/kWh, and the battery operation during peak hours allows a substantial displacement of the generator, improving efficiency and reliability. It is important to observe that all costs of energy are obtained by the LCOE approach.

These results demonstrate a clear pathway to decarbonise Caiambé's electricity system. By replacing a significant share of fossil-based generation with solar energy and storage, hybrid arrangements reduce dependence on diesel logistics, lower greenhouse gas emissions, and stabilise electricity costs. This cleaner and more reliable energy supply also creates the conditions for meeting the projected growth in local demand associated with planned social improvements in education, health care, water services, and community infrastructure.

Overall, the hybridisation of the local power system advances the objectives of SDG7 by expanding access to affordable, reliable, and modern energy while promoting low-carbon solutions. At the same time, it reinforces sustainable development in Amazonian villages by reducing environmental impacts, enhancing economic resilience, and supporting a just transition for communities located in sensitive forest regions.

Ensuring the full supply of local electricity demand is fundamental for sustaining the ongoing process of development in Caiambé. The Social Progress Index evaluation highlights structural gaps in education, health care, sanitation, communication, and opportunities, all of which depend directly on reliable energy access to reach adequate standards of service. A continuous and stable electricity supply enables schools to operate with better learning environments, supports health units with refrigeration, lighting, and medical equipment, improves water services, strengthens local commerce, and expands the economic base of the village. These improvements align with key dimensions of the SPI, particularly Basic Human Needs and Foundations of Wellbeing.

When associated with the Sustainable Development Goals, the full supply of electricity reinforces SDG3 by enabling better health conditions, SDG4 through improved access to quality education, SDG6 through better water services, and SDG8 by stimulating local economic activity and productive chains. The introduction of cleaner energy through hybrid systems adds a further qualitative dimension. Although the main priority remains the universal and reliable supply of electricity, the reduction of fossil fuel dependence and the decline in emissions provide a symbolic and practical foundation for presenting Caiambé as an example of sustainable development in the western Amazon. This cleaner energy mix strengthens SDG7 by ensuring modern and affordable electricity, while also supporting SDG13 through the mitigation of greenhouse gas emissions. Taken together, these elements show that the full electrification of the village not only sustains its embryonic urbanity but also offers a model for how Amazonian communities can integrate social progress, economic resilience, and environmental responsibility within a unified development agenda.

Although the transition to a cleaner energy mix generates clear environmental and economic benefits, it is important to recognise that, in 2025, most residents of Caiambé are not particularly concerned with whether their electricity comes from fossil fuels or renewable sources. At this stage of local development, the population is primarily focused on two immediate priorities: the cost of electricity and the stability of the supply. These concerns reflect the essential role that energy plays in daily life and in meeting basic needs, which remain at the centre of community expectations. Nevertheless, the introduction of renewable energy offers an important pedagogical opportunity. By demonstrating the advantages of cleaner technologies for long-term sustainability, local actors can promote a broader understanding of environmental stewardship, reinforce the value of nature conservation, and support more informed choices for future generations. In this sense, the hybrid system in Caiambé can serve not only as an infrastructure improvement but also as a platform for building a shared vision of sustainable development in the Amazon.

5 CONCLUSION

This study examined how electrification supports local development and social progress in a western Amazonian village through the case of Caiambé. By combining the Social Progress Index framework with field observations, technical analysis, and the concept of embryonic urbanity, the research shows that reliable electricity is fundamental for improving the quality of life in emerging settlements. Stable and affordable energy strengthens key dimensions of the SPI by enabling education, health care, water services, communication, and local commerce.

The shift from a diesel-based system to hybrid configurations produced clear environmental and economic benefits. The 300 kW solar plant reduced diesel use and emissions, and the larger configuration with 1000 kW of solar capacity and a 500 kWh battery bank further decreased fuel consumption, emissions, and energy costs. These results demonstrate that low-carbon solutions can offer cleaner, more resilient, and more affordable electricity for isolated communities.

Improved electricity access reinforces multiple Sustainable Development Goals. It supports better health and education, strengthens water services, and stimulates local economic activity. The adoption of renewable sources also contributes to climate mitigation and reduces dependence on diesel logistics. Although residents are mainly concerned with cost and supply stability, the hybrid system creates opportunities for environmental education and helps promote a broader culture of sustainability.

Finally, the findings offer relevant insights for national electrification policies. The evidence shows that hybrid solar and battery systems can reduce operational costs, increase reliability, improve social indicators, and advance decarbonization in isolated Amazonian villages. These outcomes provide practical guidance for the evolution of the Luz para Todos program and position Caiambé as a reference for developing affordable, reliable, and sustainable energy solutions across the Amazon.

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STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

The authors used ChatGPT for language editing and stylistic polishing only. All scientific content, analysis, and intellectual input were developed and verified by the authors; we take full responsibility for the accuracy and integrity of the manuscript.

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