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Field-driven multi-criteria sustainability assessment of last-mile rural electrification in Brazil

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ABSTRACT

Over the past two decades, one-sixth of the world's rural population has gained access to energy. However, intensified efforts are needed to meet the goal of universal coverage. Photovoltaic solar systems (PVS) have emerged as significant solutions for addressing last-mile electrification challenges. Nevertheless, the sustainability of PVS-based initiatives has raised concerns, and existing research lacks a long-term, practical and comprehensive program-scale assessment, along with experience-driven approaches to overcome them. This study aims to identify key design strategies to ensure the sustainable operation and impact of off-grid solar electrification programs. This work evaluates the sustainability of the world-wide referral "Luz para Todos" program in Brazil, conducting field assessments in thirty-five rural communities, electrified between 2005 and 2020 in Rio de Janeiro, Minas Gerais and Bahia. Interviews were held with beneficiaries, community leaders, rural electrification agents and key public sector actors. The quality of electricity access and the level of population's empowerment through electrification are assessed using three operation and impact criteria and two sets of ad-hoc indicators. Results highlight the importance of considering the dynamic character of energy demand and addressing additional remoteness difficulties (such as displacements and communication) to guarantee long-lasting quality PVS. Furthermore, emphasis is placed on the disruptive potential of mobile internet and the productive impact of access to water and food refrigeration in strengthening rural empowerment. This analysis serves as a guide for PVS initiative promoters to synergistically address both operational durability and long-term local development challenges.

1. Introduction

Electricity availability is fundamental for ensuring human rights, yet in 2021, 653 million people worldwide lacked access to electricity [1] and an estimated 912 million individuals relied on unelectrified health centres [1]. Moreover, those deprived of access to electricity predominantly reside in the rural regions of the Global South, which are particularly vulnerable to crisis and the adverse effects of climate change. Given that this population often exhibits a low-income socioeconomic status, they also possess limited resources for building resilience. In 2020, rural areas experienced the first increase in inhabitants without this service since 2011, a trend attributed to the Coronavirus Disease 2019 crisis [2]. In addition, 75 million individuals found themselves grappling with concerns about the affordability of electricity, thereby exacerbating their risk of energy poverty [1]. International efforts are underway to address this situation. From 2000 to 2021, 18% of the global rural population gained access to energy [2]. Nevertheless, achieving universal electricity coverage by 2030 requires

Abbreviations: BA, Bahia; IC, Impact Criteria; ICT, Information and Communication Technologies; II, Impact Indicators; LpT, in Brazilian Portuguese: "Luz para Todos"; MG, Minas Gerais; MCSA, Multi-Criteria Sustainability Assessment; Obj, Objective; OC, Operation Criteria; OI, Operation Indicators; PVS, Photovoltaic Solar System; QL, Quantitative data; QT, Qualitative data; RJ, Rio de Janeiro; SDG, Sustainable Development Goal; SIGFI, in Brazilian Portuguese: "Sistemas de Geração com Fontes Intermitentes"; TSE, in Brazilian Portuguese: "Tarifa Social de Energia"; TV, Television.

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reaching the remaining 15.5% of the world's rural population within less than a decade. This significant challenge therefore needs to improve on past efforts by intensifying rural electrification activities in the Global South [1].

As electricity coverage progresses, the most sparsely populated, geographically complex regions, which are isolated from national grids, remain without this service. These regions are commonly referred to as the last-mile of rural electrification. Inhabitants of the last-mile areas are generally low-income populations, which pose increased economic challenges for fostering electrification, as they are less attractive for investment. This adds to the complexity of electrification in the context of the emerging economies. Notably, renewable-based off-grid solutions are attracting increasing attention and are perceived as catalysts for last mile electrification [1]. More precisely, solar off-grid solutions have gained significant ground. Since 2010, financial investments in emerging economies have increasingly focused on solar energy, a trend which is primarily driven by a decrease in investment costs and the maturation of solar technology. Given their unique challenges, last-mile regions therefore need the continuity and longevity of past efforts, by ensuring the sustainability of existing initiatives [1].

Over the past last two decades (2000–2021), Latin America and the Caribbean have seen a 25.7% increase [3] in their rural electricity coverage. This region therefore boasts huge practical know-how for dealing with this challenge. In particular, Brazil, hosting 2.7% of the world's population and 1.7% of the world's territory, has faced this challenge. In 2003 Brazil launched one of the largest rural electrification programs in the world: "Luz para Todos" (LpT). More than 16 million rural inhabitants gained access to electricity through grid extension [4]. As progress was made in peri-urban and close-to-grid areas, the program directed its efforts towards reaching the most isolated populations and, in 2005, part of the LpT program was dedicated exclusively to the last-mile of rural electrification. The LpT strategy focused mainly on photovoltaic systems (PVS), called SIGFI (in Brazilian Portuguese: "Sistemas de Geração com Fontes Intermitentes"). Most of these systems were installed in the northeast (87%) and southeast (9%) regions of Brazil in 2009 [5]. However, according to official data [6,7], in 2022 only some regions maintained their activities. This means that Brazil hosts valuable knowledge regarding success and failure stories as well as the experience and know-how to face the world-wide rural last-mile challenge.

In this context, the purpose of this study is to identify the key strategies for ensuring lasting initiatives that will guarantee sustainable access to quality energy and have a positive impact on contributing to rural people's empowerment. Universal electricity coverage, fundamental for ensuring human rights and rural development, requires intensified efforts to ensure sustainable actions and knowledge sharing on PVS-based electrification. This means learning from the most experienced regions of the world that have already faced that challenge. Consequently, one of the most important rural electrification initiatives world-wide is analysed: the "Luz para Todos" program in Brazil. A multi-criteria methodology is developed. First, three ad-hoc criteria and a set of indicators are selected from each dimension (operation and impact), considering their relevance, measurability in LpT and applicability in further contexts. Then, these indicators are field-evaluated in three different Brazilian states: Rio de Janeiro (RJ), Minas Gerais (MG) and Bahia (BA). These criteria are quantified through interviews with individuals and community leaders and semi-structured interviews with distribution and implementation companies, governmental and non-governmental organizations. The two decades of practical knowledge drawn from the lessons learned from this significant case study provide meaningful insights for implementing sustainable and successful initiatives and accelerate the path toward Sustainable Development Goal nº7 (SDG7).

The work is organised as follows. Section 2 reviews related work and identifies the main gap to be addressed. Section 3 describes the rural electrification context of each region and the main strategies applied. Then, the complete sustainability evaluation methodology is presented in section 4. Section 5 outlines the results from the evaluation of the case studies. Section 6 discusses the main insights and policy implications. Finally, the principal conclusions drawn from the work are summarised in section 7.

2. Literature review

Approximately 104 million people worldwide enhanced their energy access through off-grid solar energy kits, resulting in the avoidance of 98 million metric tons of CO_2 equivalent emissions [8]. Despite the developmental and climate-resilience benefits offered by PVS, their long-term success rate and their impact on the communities they serve is highly variable. Scott-George et al. [9] review the sustainability of PVS applications for Global South rural electrification and identify the critical necessity of long-term knowledge regarding this technology. The work highlights that, while PVS can provide fast access to basic energy services, its application as a permanent solution for sustainable rural electrification requires further consideration. In fact, some authors agree that the success of PVS-based programs is relatively limited, especially in emerging economies [10].

Given the relevance of PVS for achieving last mile electrification in the Global South, there is a compelling need for further research to validate the sustainability of existing initiatives and improve future operations. In that sense, Adwek et al. [11] analyse PVS opportunities and entry barriers in Kenya, studying the best payment models and identifying the need to integrate technologies and rural electrification policies. Sovacool [12] compares, from a success and failure perspective, two World Bank PVS-based programs carried out in Sri Lanka and Indonesia. This study underscores the critical role of technological appropriation, local participation and demonstration activities. Eras-Almeida et al. [13] compare three PVS projects in South America, highlighting the main levers for sustainable electrification. These factors include appropriate policy instruments, active stakeholder involvement, lasting technological quality and locally-tailored business models. Del-Río-Carazo et al. [14] assess governance, technological and business models across environmental, economic, and social criteria. They found out the importance of fee-*as*-services models and user engagement to ensure sustainable project management. Zebra et al. [15] discusses sustainable operation of an isolated microgrid project in Mozambique. Their study centres on assessing the best design alternatives using sustainability indicators. Backer et al. [16] underscore the critical importance of economic, institutional and social enabling environments for successful off-grid energy auctions. Heinemann et al. [17] review studies addressing the transition to off-grid clean energy in Nigeria. They emphasise the need for case-by-case cost analysis and appropriate subsidies and business models. These diverse approaches to sustainable and long-lasting system operation highlight that one-fits-all solutions are no viable, and addressing this challenge requires a multi-criteria and multidimensional framework analysis.

Off-grid solutions are transformative vectors for socio-economic development [18]. Zubi et al. [19] analyse their potential in alleviating poverty in the global south and discuss the best financing options to accelerate their adoption. Aberilla et al. [20] go a step further and present a model to design and assess, from a life cycle perspective, the environmental impact of a small-scale off-grid solution for isolated communities. These two works emphasise the link between initiative design and theoretical impact. However, there are limited practical evidences regarding the impacts of these technologies. Eras-Almeida et al. [21] collect practical evidences to identify last-mile strategies through interviews with rural electrification promoters in Colombia. Jeuland et al. [22] conduct a survey with private service providers form African countries and observe gaps in market development, regulation and policy support. Lozano & Taboada [23] present a multi-criteria risk assessment for off-grid electrification in the Philippines, considering end-user perspective and identify environmental, legal, and technological factors. López-González et al. [24] compare the sustainability of two types of rural electrification alternatives applied in Cuba (PVS and diesel-based microgrids) through field research and a multi-dimensional perspective. The diversity of debate generated in these works indicates the importance of the application context and the results' path-dependency. But all coincide with the multidimensional nature of sustainability impact assessments.

These studies address sustainability evaluation from the management model and the durability of the systems' perspective [25], while others focus on the sustainable impact generated by access to energy [26]. However, these two aspects are rarely dealt with together. Within the second category, most works discuss some social repercussions qualitatively, but do not assess the full impact of last-mile electrification programs nor prioritise metrics to quantify the sustainability of initiatives based on the users' perspective. Furthermore, despite the fact that these systems can reach a life span of 20 years, most of the works assess PVS installed less than a decade previously [9]. Additionally, most evaluations focus on individual projects, while scaling up programs presents unique sustainability challenges. According to Hellqvist & Heubaum [27], the Bangladesh PVS program is at risk of collapsing after decades due to issues in market development and a weak institutional framework. Juanpera et al. [28] discuss the importance of a well-defined maintenance plan to ensure the long-term success of stand-alone initiatives in Peru. These works highlight the need to address program's sustainability and durability through field research, that include quantitative data and address long-term rural electrification outcomes. Additionally, it should be taken into account that the point of view of all the stakeholders allows for greater subjectivity in the comparative analysis and extraction of the lessons learned [29]. Although off-grid energy solutions are increasing, the socioeconomic complexity of access-deficit countries makes it difficult to track progress towards electrification. Therefore, access to electricity should be defined and measured considering the nature and degree of access from a multi-criteria perspective, to help governments understand their access status, identify any bottlenecks and take informed decisions to achieve their universal access goals more efficiently [1].

Despite the importance and worldwide recognition of the LpT program, its last-mile application has been little discussed in scientific studies. At the beginning of the LpT program, the research focused on the techno-economic feasibility of off-grid solutions, comparing various technologies [30] analysing different autonomies [31] or comparing individual and micro-grid configurations [32]. Later, Moraes et al. [33] discussed the possibility of cooling with different PVS capacities. As the electrification efforts have been directed towards the Amazon region, the analyses related to the LpT program have followed the same path. Gómez & Silveira [34] assess the institutional and financial framework for electrifying the Brazilian Amazon and highlight the importance of site-specific off-grid solutions. The legal-institutional context of the LpT program is further analysed by national organizations, in order to identify barriers and levers for universalization [35]. Other authors assess specific projects in the field in different Legal Amazon states, such as Acre [36], Pará [37] and Amapá [38]. These works focus on the short-term evaluation of local implementation and management strategies. In particular, Fonseca et al. [38] conclude that the same mistakes of previous national rural electrification programs have been repeated. In the same vein, Valer et al. [39] compare lessons learned from 5 year-old PVS electrification in the Amazon and São Paulo states. As observed, only short-term evaluations focusing on local case studies have been carried out, especially in the Amazon region. However, last-mile activities have never been practically evaluated in the long term.

This works is based on three research hypotheses. First, it posits that off-grid solutions, particularly stand-alone PVS, are one of the only viable solutions for addressing the challenges of rural last-mile electrification, which is a universal concern. Second, it asserts that improved design strategies in off-grid solar electrification programs can substantially enhance long-term sustainability. Third, it suggests that the LpT program in Brazil exhibits varying levels of sustainability in rural electrification across different regions, which could be influenced by local factors. This study aims to fill a significant research gap, by performing a comprehensive field evaluation of the regional application of the LpT program in the northeast and southeast of Brazil. The primary contribution of this work is in addressing the absence of long-term practical evidences derived from program-scale experiences. The innovative aspects of this research lie in its simultaneous evaluation of operational sustainability and impact sustainability while establishing connections with program design. Lessons learned are fundamental for reproducing the successes and facing the challenges of past experiences. The multi-criteria regional analysis conducted in one of the world's largest countries provides therefore, holistic insights into key strategies for enhancing solar off-grid sustainable rural electrification.

3. Case studies

The LpT program was deployed in Brazil aiming to electrify rural areas and foster social development among low-income communities. This program therefore accumulated two decades of valuable experience in long-lasting solar off-grid electrification strategies for rural empowerment. A comprehensive multiple case study was conducted across three different Brazilian states: Rio de Janeiro (RJ), Minas Gerais (MG) and Bahia (BA), all situated in the northeast and southeast regions, where most SIGFI were implemented. Due to Brazil's vast territory, diverse cultures, climates, and numerous stakeholders, LpT design and implementation varied among these regions, leading to distinct durability and impacts on beneficiaries. Notably, only RJ and BA are continuing their activities in 2022 [7]. The complementarity and relevance of these case studies offer invaluable insights for future solar off-grid electrification initiatives.

The following sections present the main characteristics of RJ (section 3.1), MG (section 3.2) and BA (section 3.3), including the rural electrification context, beneficiary profiles and regional attributes. Figs. 1–3 provide community-specific information, incorporating both publicly available research and input from interviewed rural electrification actors.

3.1. Rio de Janeiro (RJ)

Between 2001 and 2013, the state of RJ increased its rural electricity coverage from 99.3% [40] to 99.9% [41]. Enel Distribuição Rio (Ampla until 2018), one of the main private capital energy distributors in this concession area, assumed the state last-mile electrification. Enel's involvement with the LpT program began in 2007, with the approval of 55 systems with a capacity of 13 kWh/month, known as SIGFI13 [42]. However, these systems encountered issues in the same year [6]. Over the subsequent years, 1741 SIGFI13 were planned but never installed due to environmental licensing challenges [43–45]. In 2020, the outsourced company DR Energia won a public tender that was launched to provide energy access to the remaining 1000 households lacking this service. Only 15.8% of them met the environmental license conditions and 4% had been electrified at the time of the visit, all of whom have been field-assessed.

Fig. 1 illustrates the 5 communities benefiting from the program (RJ1-RJ5), situated in the municipalities of Paraty and Angra dos Reis. RJ1 is an indigenous community of the Guarany M'Bya ethnic group, primarily engaged in indigenous handicrafts, with most indigenous families also receiving cash transfer subsidies. The rest of the communities (RJ2-RJ5) are caiçara communities, the traditional inhabitants of the south-eastern and southern coast of Brazil, primarily involved in artisanal fishing and community ecotourism. All of these communities are located within the Atlantic Forest biome and are accessible either by boat (RJ2-RJ5), or by footpaths (RJ1-RJ3).

All of the communities received SIGFI80 systems, capable of

COMMUNITIES DATA:

ID	Community	Municipality	Households	Schools	Instal. date
			Quantity & Capacity (last available data: 2021)		
RJ1	Aldeia Araponga	Paraty	12 SIGFI80	1 SIGFI80	2020
RJ2	Cairuçu das pedras	Paraty	6 SIGFI80	-	2020
RJ3	Martim de Sã	Paraty	5 SIGFI80	-	2020
RJ4	Ilha Itacá	Paraty	1 SIGFI80	-	2020
RJ5	Ilha da Gipoia	Angra dos Reis	13 SIGFI80	-	2020

RURAL ACTORS DATA:
Distribution company: Enel Distribuição Rio (Ampla until 2018)
Implementation company: DR Energia

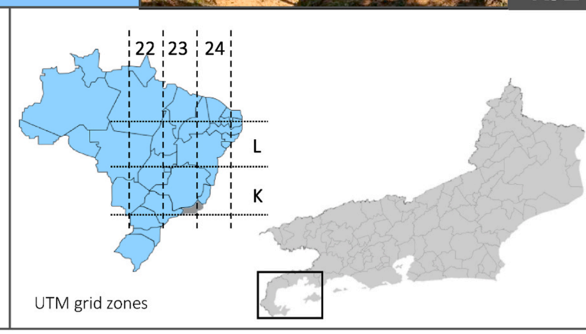


Fig. 1. Location of the field-assessed communities in Rio de Janeiro (RJ). The systems' information has been gathered during interviews with DR Energia (2021). The photographs show the systems installed in households in the indigenous community RJ1 and the caiçara village RJ2 (SIGFI80: stand-alone photovoltaic systems of 80 kWh/month).

generating 80 kWh/month to power households and the indigenous school. DR Energia's primary strategy involved deploying robust, low-maintenance and long-lasting systems through oversizing batteries and using climate-resistant materials. The photovoltaic systems were compactly installed outside the houses, and households received an internal installation kit tailored to local conditions. At the time of the visits, the maintenance of the systems was within its warranty period, under the responsibility of the installation company. The maintenance plan included annual preventive activities and corrective maintenance upon user request, as well as equipment disposal procedures for both practices. Enel technicians performed the bimonthly reading of the electricity meter, with energy tariffs varying based on consumption. System implementation also included community training on circuit breaker operation, information regarding rational energy use, guidelines on equipment connectivity (depending on the system's capacity) and awareness of the need to clean the photovoltaic panels.

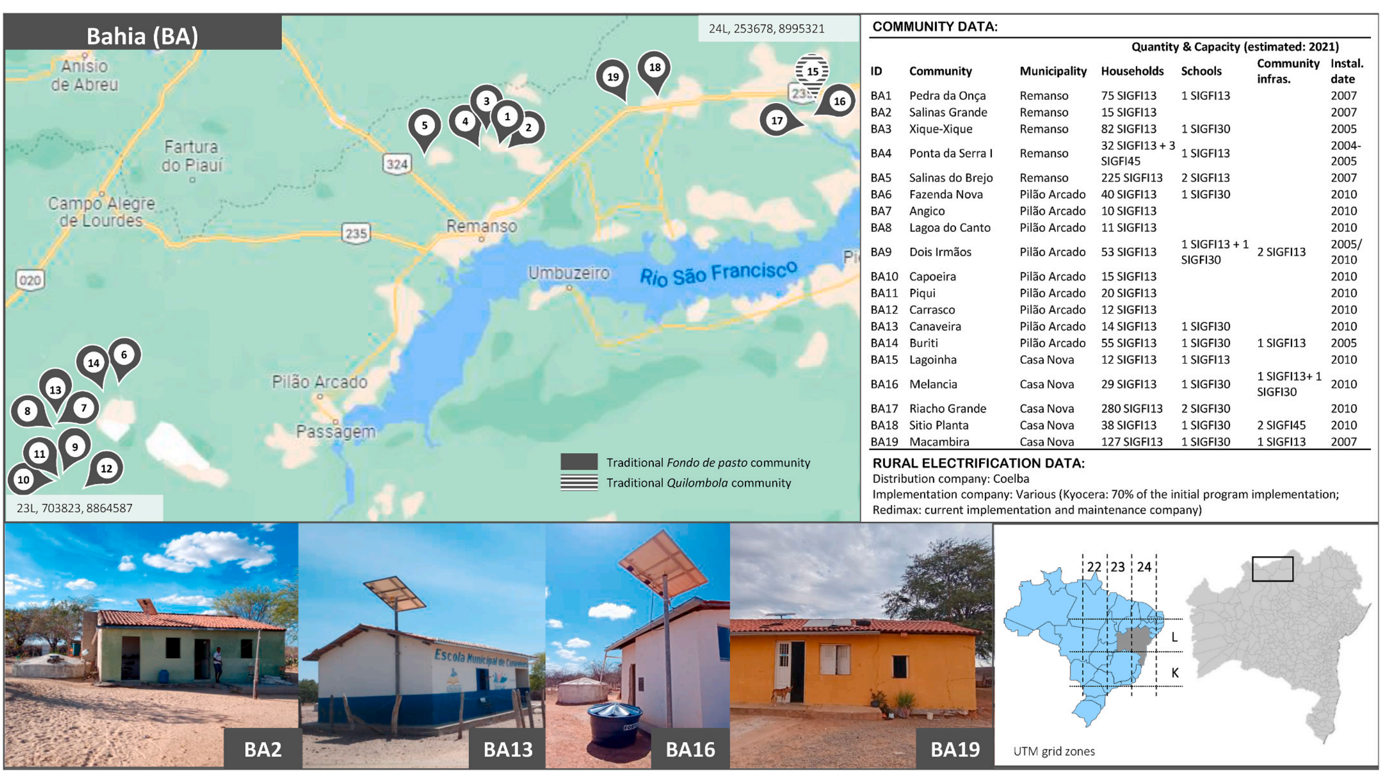
3.2. Minas Gerais (MG)

MG Rural electricity coverage has increased from 97.7% in 2001 [40] to 99.9% in 2013 [41]. The private company Cemig is the major state energy provider and has been historically in charge of last-mile electrification initiatives, including the LpT program [48]. Cemig performed a pre-electrification strategy, focused on rapidly installing low-power and cost-effective systems in remote low-income populations. In 2005, 338 systems were installed in public buildings (mainly schools and some community buildings). In 2007, 1332 systems were installed in households. By 2009, 92% of the installed systems were operational [43,44], primarily in the Jequitinhonha and Norte de Minas mesoregions. Together, these areas accounted for 93% of all residential systems, 91% of schools' systems and all of the community systems [46,47]. After 11 years, lacking official data, the remaining systems were identified through consultation with Cemig experts and field visits were conducted in the beneficiary communities.

Fig. 2.1 shows the first region, Mata dos Crioulos, situated in the Jequitinhonha river valley between three protected areas of the Cerrado biome and inhabited by the remaining "garimpeiras" communities (MG1-MG3). These traditional populations, formerly engaged in mineral extraction, transitioned to family agriculture and livestock when their traditional activities became illegal [49]. The second region, shown in Fig. 2.2, corresponds to the São Francisco river, in Norte de Minas. This area features a mixture of Cerrado and Caatinga biomes and is predominantly inhabited by traditional "vazanteiras" communities practicing agriculture associated with the river's cycles and traditional fishing (MG4-MG11). This region also includes agrarian reform settlements (MG11), legalised rural property occupations dedicated to family farming. In both regions, some inhabitants identify as "quilombolas", descendants of former African slaves, primarily engaged in subsistence

			Quantity & Capacity (last available data: 2010)			
ID	Community	Municipality	Households	Schools	Community infrastructure	Instal. date
MG1	Acaba Mundo	Diamantina	9 SIGFI13	-	-	2006
MG2	Algodoeiro	Diamantina	33 SIGFI13	1 SIGFI30	1 SIGFI13	2006
MG3	Covão	Diamantina	28 SIGFI13	1 SIGFI13	-	2006
MG4	Jatobá – Vila Nova esperança	Januária	22 SIGFI13	-	-	-
MG5	Ilha do Amargoso – Riacho Novo	Januária	36 SIGFI13	-	-	-
MG6	Ilha do Retiro	Itacarambi	52 SIGFI13	1 SIGFI30	1 SIGFI13	2006-2008
MG7	Ilha Maria Preta	Itacarambi	94 SIGFI13		1 SIGFI13	2005-2006
MG8	Ilha do Capão	Itacarambi	53 SIGFI13	1 SIGFI45	-	2008-2009
MG9	Ilha Jenipapo	Itacarambi	36 SIGFI13	1 SIGFI45	-	2005-2006
MG10	Ilha da Ressaca – Quilombo da Lapinha	Matias Cardoso	49 SIGFI13	1 SIGFI30	-	2005-2006
MG11	Ilha Curimatá – Assentamento Mãe Romana	Manga	50 SIGFI13	1 SIGFI30	1 SIGFI13	2005-2006

Fig. 2. Location of the field-assessed communities in two regions of MG: A- Mata dos Crioulos (Jequitinhonha); B-São Francisco river (Norte de Minas). The systems' information was collected during interviews with Cemig representants and is based on the last maintenance database [46,47]. The photographs show the systems installed in households (MG2, MG4 and MG6). The MG2 system has been adapted with car batteries, MG4 suffered from a regional robbery and the electronic equipment of MG6 has been transferred inside the house to prevent theft (SIGFI13-SIGFI30: stand-alone photovoltaic systems of 13–30 kWh/month).



			Quantity & Capacity (estimated: 2021)			
ID	Community	Municipality	Households	Schools	Community infras.	Instal. date
BA1	Pedra da Onça	Remanso	75 SIGFI13	1 SIGFI13		2007
BA2	Salinas Grande	Remanso	15 SIGFI13			2007
BA3	Xique-Xique	Remanso	82 SIGFI13	1 SIGFI30		2005
BA4	Ponta da Serra I	Remanso	32 SIGFI13 + 3 SIGFI45	1 SIGFI13		2004-2005
BA5	Salinas do Brejo	Remanso	225 SIGFI13	2 SIGFI13		2007
BA6	Fazenda Nova	Pilão Arcado	40 SIGFI13	1 SIGFI30		2010
BA7	Angico	Pilão Arcado	10 SIGFI13			2010
BA8	Lagoa do Canto	Pilão Arcado	11 SIGFI13			2010
BA9	Dois Irmãos	Pilão Arcado	53 SIGFI13	1 SIGFI13 + 1 SIGFI30	2 SIGFI13	2005/2010
BA10	Capoeira	Pilão Arcado	15 SIGFI13			2010
BA11	Piqui	Pilão Arcado	20 SIGFI13			2010
BA12	Carrasco	Pilão Arcado	12 SIGFI13			2010
BA13	Canaveira	Pilão Arcado	14 SIGFI13	1 SIGFI30		2010
BA14	Buriti	Pilão Arcado	55 SIGFI13	1 SIGFI30	1 SIGFI13	2005
BA15	Lagoinha	Casa Nova	12 SIGFI13	1 SIGFI13		2010
BA16	Melancia	Casa Nova	29 SIGFI13	1 SIGFI30	1 SIGFI13+ 1 SIGFI30	2010
BA17	Riacho Grande	Casa Nova	280 SIGFI13	2 SIGFI30		2010
BA18	Sitio Planta	Casa Nova	38 SIGFI13	1 SIGFI30	2 SIGFI45	2010
BA19	Macambira	Casa Nova	127 SIGFI13	1 SIGFI30	1 SIGFI13	2007

Fig. 3. Location of the field-assessed communities in BA. The systems' information was gathered during visits (2021). The photographs show systems installed in households (BA2, BA19), in a school (BA13) and in a fruit processing community centre (BA16). BA19 has been improved with additional PV panels (SIGFI13-SIGFI45: stand-alone photovoltaic systems of 13–45 kWh/month).

agriculture (MG1-MG3, MG10).

All households and community infrastructure received SIGFI13 systems, capable of generating 13 kWh/month. Cemig explicitly considered this capacity to ensure both payment capacity and access to tariff discounts. In schools, which relied on municipal budgets, more powerful systems were installed (mostly SIGFI60 or SIGFI45). Various companies (OAS, Odebrecht, Andrade Gutierrez) were involved and all the installations were positioned outside the houses and equipped with circuit breakers and protection mechanisms. Users received initial explanations on the systems' operation and rational energy use. The maintenance plan included corrective maintenance upon user demand and disposal practices. Payment consisted of a fixed monthly fee. However, despite Cemig's prior experience, the distribution company encountered several challenges, including high non-payment rates, regional theft, flooding and inverters burning out due to the arid climate. Additionally, the expansion of the state power grid, coupled with the growth of more densely populated communities, rendered many last-mile regions eligible for grid electrification, while less-populated communities and small rural schools were disappearing.

3.3. Bahia (BA)

BA state experienced significant progress towards rural electrification, with rural coverage increasing from 86.8% in 2001 [40] to 98.9% in 2013 [41]. Most of the state is under the concession of the private energy distribution company Coelba, which has been leading last-mile electrification efforts since 1998. Coelba developed the first guidelines for the official use of SIGFI as a technology for energy universalization and adopted it as its own business strategy [50]. From 2006 to 2014, 20,891 SIGFIs were installed throughout the state, with 70% still operating in 2020. The highest concentration of systems is located in the region affected by the Sobradinho hydroelectric plant, one of the program's eligibility criteria, situated in the northern part of the state. Specifically, the municipalities accounting for a quarter of all SIGFIs have been field-assessed.

Fig. 3 shows the communities visited within the municipalities of Casa Nova, Remanso and Pilão Arcado. These regions, marked by drought, are inhabited by the traditional "fundo de pasto" communities, who raise small animals, mainly goats and cattle, which graze freely on the local vegetation. Their main productive activities include family farming, beekeeping, livestock rearing and local fruit processing. Brejo region also relies on sugar cane production. In addition, some communities identify themselves as "quilombola" populations (BA15).

Approximately 98% of the systems are SIGFI13, capable of supplying 13 kWh/month, and 2% are SIGFI30, which can provide 30 kWh/month. Over 99% of the systems have been installed in households [6,7]. Coelba employed a standardization strategy, sizing all the systems based on the state's average irradiation and latitude and outsourced the installation service at a "turn-key" price for any location within the state. About 65% of the systems were installed by the Kyocera company. Photovoltaic panels were installed on the roof, while electronic and electrochemical equipment was placed inside the houses. An internal installation kit was donated during the systems' installation, which included a ventilation system through the electrical conduit to the ceiling to vent potential battery gas leaks. Brief explanations on the correct use of the systems were provided in an orientation portfolio. After the 3-year warranty period, Coelba assumed maintenance activities, mainly corrective and upon user's demand. Various strategies were considered, ranging from collective training of all technicians (resulting in quick but poor quality response) to specialised technical teams solely for photovoltaic solar energy (resulting in higher quality but longer response times). The installation and maintenance tasks were later outsourced, with periodic renewal of the companies in charge. Discarded parts were removed during maintenance activities and collected by the suppliers. The residential payment mechanism involved a fixed monthly fee of 13 kWh/month at the distributor's kWh price, and lower-income families were eligible for rate discount.

4. Methodology

This section describes the methodology developed for assessing the long-term sustainability of the LpT last-mile program. Section 2.1 introduces the multi-criteria sustainability assessment (MCSA) tool considered and demonstrates its suitability and relevance. The MCSA structure and the field research procedure are also explained. Section 2.2 lists and describes the criteria contemplated for a comprehensive multi-case study analysis, along with the selected indicators to measure and evaluate the program's operational and impact sustainability. Lastly, section 2.3 provides a detailed description of the interview process, including the method and contents, the target users and their profiles in each region, and the data analysis procedure.

4.1. MCSA justification and structure

This study assesses the long-term sustainability of the LpT program in Brazil, a global referral initiative focusing on last-mile rural electrification. It addresses a notable research gap (as discussed in section 2), where off-grid electrification solutions are typically evaluated at local or national levels, but leaves a knowledge void regarding program designs, regional implementation and operation, and their enduring impacts on beneficiaries. To bridge this gap, this research develops a multi-criteria decision analysis tool particularly focused on assessing sustainability, the MCSA method.

Multi-criteria decision analysis tools facilitate tackling complex decision challenges by breaking them down into manageable components [51]. This approach has found extensive use in studies that examine the interplay between sustainability and electrification, due to its ability to address conflicting objectives [52]. This method is particularly useful for identifying synergies and trade-off between energy systems' policies and their impact on society [53]. The application of multi-criteria decision analysis tools to evaluate complementary case studies is especially valuable in explanatory studies within the social sciences of energy, helping generate hypotheses and providing broader generalisation [12]. Moreover, the spatial variation between cases highlights differences and improves understanding of complex variables. Numerous works have contributed to designing multi-criteria decision analysis models explicitly for sustainability assessment. For instance, Bhandari et al. developed sustainability assessment tools to evaluate the operational sustainability of micro-hydropower plants in Nepal [54] and to identify suitable and accessible energy generation solutions for Niger [55]. Runsten et al. introduced a multi-criteria sustainability analysis method to assess energy provision in informal settlements in South Africa [56]. These works underscore sustainability's multi-level nature, emphasizing the interplay between local and global factors, path-dependency and site-specific characteristics.

A focus on developing data-driven multi-criteria decision-making tools has emerged, incorporating post-analysis data to formulate criteria and indicators. Examples include a data-driven energy planning framework for generation expansion strategies in developing countries [57] and a data-driven analytical road-map for renewable microgrid development in South Korea [58]. Field-work-derived data is gaining prominence, incorporating ad-hoc criteria and indicators, particularly in South American countries. Field-driven multi-criteria research developed in Peru, Ecuador and Bolivia [59] highlights the relevance of comparative case studies for evaluating the sustainability of different energy management models. This perspective is echoed in Peru [28] and Venezuela [60] concerning long-term sustainability for rural electrification initiatives. Both quantitative and qualitative field-driven indicators and criteria are considered for gender-inclusive assessments in Venezuela [61] and Brazil [62]. These studies collectively underscore the significance of field-driven ad-hoc indicators and criteria, defined through interviews with key stakeholders to integrate their perspective into the assessment or decision-making process, including local, and particularly traditional, knowledge.

The MCSA framework is presented in Fig. 4 and is structured in three main steps: 1) defining the purpose and alternatives for comparison; 2) Identifying criteria and indicators according to the decision-making problem; 3) assessing indicators, aggregating results and discussing their implications.

In this work, three case studies are considered (step 1, Fig. 4), corresponding to the regional application of the LpT program in RJ, MG and BA (see Section 3), enhancing a comparative holistic evaluation [29,59]. The MCSA method aims to capture the primary strategies deployed in the three study regions, their long-term operations and their impacts on beneficiaries. It revolves around the premise that sustainable rural electrification programs should achieve two main objectives. The first is to build technical solutions that ensure sustainable energy access for all beneficiaries, maintaining consistent quality (obj1), while the second is to enhance the sustainable empowerment of the rural population through energy access (obj2). These design objectives, supported by the literature review presented in section 2, have implications for both operational guidelines and potential program impacts.

A set of ad-hoc field-driven indicators (step 2, Fig. 4) established for each objective, to serve as a metric for the evaluation criteria. These criteria and indicators are comprehensively detailed in section 4.2. Evaluation criteria and preliminary indicators were carefully selected, considering an exhaustive scientific research review, compiling indicators used in similar scientific works and short-listing the most relevant indicators that are systemic, consistent, independent, measurable and comparable. These indicators guided the development of the questionnaires employed for conducting field interviews (see section 4.3). Following data-driven multi-criteria methods [57–62], a post-analysis of the field results was performed, further enhancing the identification of the most relevant comparative indicators. These were shortlisted into a holistic and concise set of qualitative and quantitative indicators. The selected indicators underwent validation by expert academics and professionals specializing in sustainable MCSA applied to rural electrification initiatives in the Global South.

Finally (step 3, Fig. 4), the selected indicators and criteria are assessed in each regional case study through interviews with key stakeholders, as further explained in section 4.3. The results obtained are analysed individually and aggregated by criterion, calculated according to the average value of all normalised indicators. Aggregated results enhance the comparison of alternatives through a results matrix, while individual results permit a nuanced discussion in relation to the operational and impact objectives [59,60,62]. These steps collectively lead to building meaningful insights to foster the sustainability of future last-mile electrification initiatives.

4.2. Criteria and indicators

Fig. 5 provides an overview of the MCSA method developed in this study, illustrating the interlinkages between program design, operation and impact. The sustainability assessment of the LpT program is conducted within this framework, focusing on two design objectives that encompass operation and impact dimensions. These objectives are measured using three evaluation criteria, detailed in Tables 1 and 2

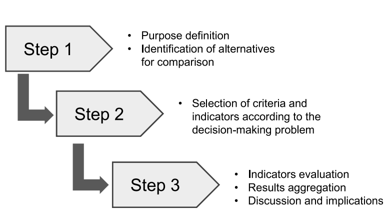


Fig. 4. Multi-Criteria Sustainability Assessment (MCSA) framework based on a 3-step structure.

respectively. Appendix A provides a table showing the relevance of each criterion, demonstrating its inclusion in comparable research studies. The primary category of indicators utilised to measure these criteria is also listed.

Achieving sustainable access to quality energy (Obj.1) entails considering three fundamental pillars: an adequate maintenance plan (OC1), a certain degree of local involvement (OC2) and a locally appropriate payment system (OC3). A robust maintenance plan is required, to guarantee the proper technical condition of the systems (OI1.1-OI1.5) over the desired timeframe, with quality activities (OI1.6-OI1.7) carried out frequently (OI1.8-OI1.9). Effective communication channels between users and rural electrification agents (OI1.10-OI1.11) and proper disposal practices (OI1.12) are also necessary. In addition, managing distributed energy resources requires a certain level of local participation. A successful participatory model depends on factors such as equity in program access (OI2.1-OI2.2), the quality of beneficiary training (OI2.3-OI2.6) and progress in developing operation and management (O&M) skills (OI2.7-OI2.8). Finally, the tariff mechanism warrants in-depth analysis to identify whether this price is affordable (OI3.1-OI3.3), fair, and consistent with the service provided (OI3.4-OI3.6).

Increasing people's empowerment (Obj.2) through rural electrification requires addressing several fronts: psychological growth (IC1), physical improvement (IC2) and socio-economic development (IC3). Information and communication technologies (ICTs) (II1.1-II1.4) can facilitate social interactions, provide knowledge and promote culture. Home and school education (II1.5-II1.7) are the basis of intellectual and psychological growth, with the quality of education closely tied to access to energy. Health is a key element for the social well-being and physical improvement of the populations. Access to energy allows meeting medical needs (II2.1-II2.3) and reduces polluting practices in the households (II2.4-II2.5). Socio-economic development is fundamental for rural empowerment and can be measured by analysing new productive activities enabled by energy access (II3.1-II3.3). Evaluating the extent of unsatisfied energy needs also helps in identifying the magnitude of the existing energy poverty gap (II3.4-II3.5).

4.3. Interview description

The experiences of the most relevant actors were considered in order to evaluate the sustainability of the Brazilian last-mile electrification initiative. Ninety-four interviews were conducted with beneficiaries and community leaders. The field work included four face-to-face meetings with rural electrification agents and twenty-one consultations with representatives of governmental organizations, municipalities, social assistance centres, local non-governmental organizations and civil society organizations. The diversity of respondent profiles aims to comprehensively capture the full reality by spanning all the stakeholders' perspectives. The data collection process spanned from February to September 2021.

To gain insights from the beneficiaries' perspective, two types of interviews were conducted. Thirty-five semi-structured community interviews involved discussions with community leaders, including indigenous community religious leaders, presidents of community associations and local organizations and individuals esteemed as community leaders by the community inhabitants. These representatives played a historical role in the village's development processes, including electricity access infrastructure. These interviews, included in Appendix B, aimed to gather general information about the number, application and status of installed systems in their community. Details about existing community infrastructure, users' profiles, systems' technical data, training types and perceptions of the maintenance plan were also collected. Additionally, fifty-eight individual structured interviews, presented in Appendix C, provided specific information on user's consumption patterns, their opinions on system quality and management and their perception of the main program's benefits. Interviews utilised

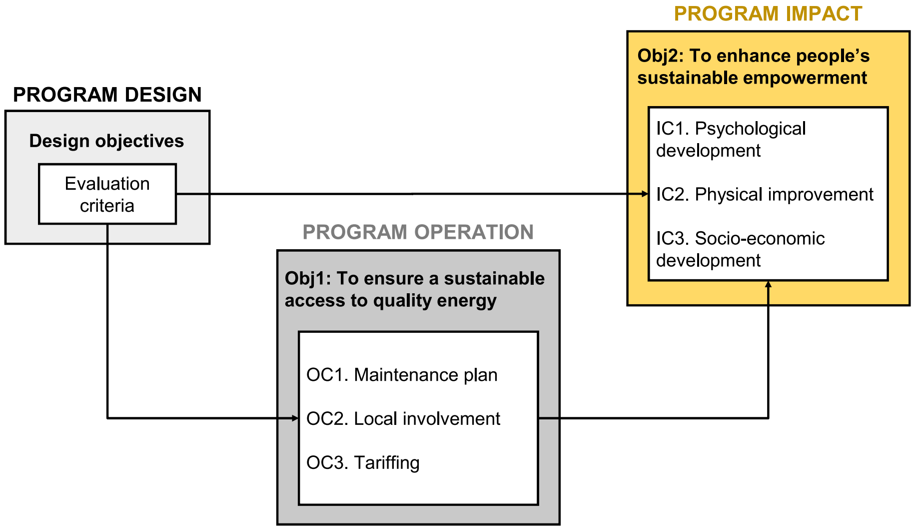


Fig. 5. LpT assessment scheme, based on two design objectives for sustainable program operation (Obj1) and sustainable program impact (Obj2) (Obj: objective; OC: operation criteria; IC: impact criteria).

Table 1
Description of operation criteria, sub-criteria and indicators (OC: operation criteria; OI: operation indicators; QL: qualitative data; QT: quantitative data; + to maximise/- to minimise).

		Indicators (I)		QL/QT	+/-
OC1. Maintenance plan	Technical condition of the systems	**OI1.1**	General operating condition of the systems	QT	+
		OI1.2	Beneficiaries' satisfaction with the program execution	QT	+
		OI1.3	Beneficiaries' general satisfaction with the program	QT	+
		OI1.4	Beneficiaries' perception of energy availability	QT	+
		OI1.5	Beneficiaries' perception of energy availability during rainy days	QT	+
		OI1.6	Beneficiaries' perception of maintenance quality	QT	+
		OI1.7	Presence of protections and circuit breakers in the community	QT	+
	Frequency of maintenance	**OI1.8**	Beneficiaries' perception of maintenance frequency	QT	+
		OI1.9	Average time of service interruption waiting for maintenance according to field reality	QT	–
	Communication with beneficiaries	**OI1.10**	Beneficiaries' perception of the quality of the communication channel with the installation company	QT	+
		OI1.11	Beneficiaries' perception of the quality of the communication channel with the distribution company	QT	+
	Disposal strategy	**OI1.12**	Potential battery-related socio-environmental risk due to maintenance malpractices and disposal	QL	–
OC2. Local involvement	Equity in program access	**OI2.1**	Beneficiaries' perception of equity in the program access	QT	+
		OI2.2	Beneficiaries' perception of equity in the capacity installed	QT	+
	Capacitation of beneficiaries	**OI2.3**	Beneficiaries considering they received capacitation	QT	+
		OI2.4	Beneficiaries' perception of equity in the capacitation activities	QT	+
		OI2.5	Beneficiaries' perception of the quality of the capacitation	QT	+
		OI2.6	Beneficiaries' perception of the intelligibility of the booklet	QT	+
	Development of O&M skills	**OI2.7**	Beneficiaries who have succeeded in self-management	QT	+
		OI2.8	Beneficiaries who still remember what they learned	QT	+
OC3. Tariff	Electricity tariff	**OI3.1**	Average energy cost per kWh without discounts	QT	–
		OI3.2	Average energy cost per kWh with discounts	QT	–
		OI3.3	Additional costs to the bill for administrative reasons	QT	–
	Fairness and default rate	**OI3.4**	Beneficiaries' perception of tariff according to the service supplied	QT	+
		OI3.5	Beneficiaries paying promptly	QT	+
		OI3.6	Availability of TSE regarding family salary	QT	+

a non-random, quota and snowball sampling method, where each actor interviewed successively facilitates contact with another beneficiary. This non-probabilistic sampling approach ensured gender representation equality and has proven benefits for reaching hard-to-access populations [63]. Furthermore, the snowball sampling methods facilitated the inclusion of a diverse range of respondent profiles, ensuring that those interviewed were relevant for the research, as they were selected by the communities themselves [64,65]. Interviews with both community representatives and with beneficiaries were held in face-to-face meetings in the communities, lasting approximatively 1–2 h. This method enhanced personal interactions, capturing comprehensive verbal and non-verbal communications and promoting the inclusive and accessible participation of individuals with different profiles (age, gender, profession, community role). For instance, as presented in Appendix C, figures were used for guiding the Likert scale-based responses. Likert scales are rating scales used to measure opinions and behaviours [66]. The figure-based technique aimed to aid non-literate participants in explaining their perception of improvements. Informed consent was obtained from all the participants and ethical guidelines were considered throughout the interview process. The corresponding author transcribed all the data from the interviews, relying on questionnaires, additional field notes, photographs and GPS coordinates to ensure the precision required for data interpretation [67]. The collected mixed data underwent a two-step analysis. First, all the quantitative data was

Table 2
Description of impact criteria, sub-criteria and indicators (IC: impact criteria; II: impact indicators; QL: qualitative data; QT: quantitative data; + to maximise/- to minimise*)*.

		Indicators (I)		QL/ QT	+/-
IC1. Psychological development	ICTs	II1.1	Beneficiaries who mentioned each type of ICTs improvement	QT	+
		II1.2	Phone signal access in the communities	QT	+
		II1.3	Internet access in the communities	QT	+
		II1.4	Beneficiaries' perception of ICTs improvement due to the program	QT	+
	Education	**II1.5**	Main reported energy-related education improvement at school	QT	+
		II1.6	Beneficiaries' perception of education improvement in the school due to the program	QT	+
		II1.7	Beneficiaries' perception of general education improvement in the community due to the program	QT	+
IC2. Physical improvement	**Health service**	**II2.1**	Health-related energy needs covered at household level	QL	+
		II2.2	Beneficiaries' perception of energy availability for health needs	QT	+
		II2.3	Communities with, at least, internal and regular medical assistance	QT	+
	Contamination reduction	**II2.4**	Reduction of pollution in household lighting due to the program	QT	+
		II2.5	Beneficiaries' perception of contamination reduction due to the program	QT	+
IC3. Socio-economic development	**Development of productive activities**	**II3.1**	Means of supplying the energy needs for productive activities	QT	+
		II3.2	Beneficiaries' perception of productivity improvements	QT	+
		II3.3	Beneficiaries' perception of energy availability for productive activities	QT	+
	Poverty alleviation gap	**II3.4**	Beneficiaries repressed energy needs	QT	–
		II3.5	Percentage of beneficiaries needing extra energy to cover their needs	QT	–

evaluated through a comparative regional analysis. Secondly, qualitative data was transcribed and interpreted using a thematic analysis approach to identify recurring patterns, allowing for a nuanced understanding of the varied perspective obtained during the interviews [62].

Given that field work was conducted in traditional communities, consultations were also held with official governmental and non-governmental organizations to ensure sensitivity and respect towards these populations. In RJ, the local regional coordinator of the National Indigenous Foundation of Brazil (FUNAI, in Brazilian Portuguese: "Fundação Nacional dos Povos Indígenas") was interviewed. In MG, consultations were conducted with the reference centre for social assistance (CRAS, in Brazilian Portuguese: "Centro de Referência da Assistência Social") of Diamantina, Januária and Itacarambi, along with discussions with the secretary of public works of Diamantina, the Januária fishermen's colony ("Colônia de pescadores de Januária") and the Itacarambi rural workers' association ("Associação dos Vazanteiros de Itacarambi*")*. The secretary of education of the municipality of Bonito de Minas (MG) provided insights into the educational situation in the Coronavirus Disease 2019 context, with support from the State Forest Institute (IEF, in Brazilian Portuguese: "Instituto Estadual de Florestas"). The SASOP organization (in Brazilian Portuguese: "Serviço de Assessoria a Organizações Populares Rurais"), the Secretary of Agriculture of the municipality of Remanso and the SAJUC organization (in Brazilian Portuguese: "Serviço de Assistência Socioambiental no Campo e Cidade") played significant roles in locating and visiting the beneficiary communities of BA. These interviews were held in-person, spanning variable durations according to the respondents' involvement and information provided, ranging from 30-min sessions to 4-h meetings. The respondents' profiles included individuals with the most expertise on the topics, as indicated by their respective organizations. Meetings were scheduled to accommodate their availability and ongoing contact has been maintained. Some of these experts have validated the main findings of this work.

The rural electrification agents interviewed included the CEO of the installation company DR Energia in RJ, the technical specialist in electrical systems at Cemig in MG and the manager of Coelba's rural electrification scheme in BA. All of them actively participated in the program design, implementation and monitoring throughout the study regions. Additional inputs were gathered from the manager of the BA maintenance company, Redimax. The semi-structured interviews addressed the institutional context, the technologies considered (energy resources, capacities and the internal installation kit), the demand identification process (selection criteria, socioeconomic profiles and community locations), economic data on tariffs and system costs, the implementation process, capacitation content and the applied maintenance plans. These interviews also featured critical discussions of the main challenges faced during the regional implementation of the LpT program, the primary sources of system failures and the program's general limitations in achieving universal electricity coverage. These interviews were conducted in-person, with meetings ranging from 2 to 5 h. The respondents are among the most involved experts from the companies that have worked in the field developing rural electrification solutions for these last-mile communities. Meetings were scheduled to align with their availability, and ongoing contact has been maintained. These experts have validated the main findings of this work.

5. Results

This section assesses the long-term regional sustainability of the LpT program, considering all the stakeholder perspectives collected during field research. An overview of the rural electrification actors' experiences and the existing research (see section 3) shows a late (<1 year) and high-capacity electrification (SIGFI80) for a limited group in RJ, an abandoned (last activity in 2010) pre-electrification policy (SIGFI13) in MG, and an effective (activities since 2004) low-capacity rural electrification in BA.

In more depth, the indicators presented in section 3 reflect the viewpoints of beneficiaries and community leaders. Fig. 6 outlines the main sustainability scores obtained in each study region. Regarding operations, RJ performs better in terms of the maintenance plan (OC1) and local involvement (OC2), while MG and BA obtained greater results in the tariff mechanism (OC3). The most positive impact is observed in RJ, in relation to the physical improvement of beneficiaries (IC2). The psychological development (IC1) is headed by MG and BA and the best socio-economic development (IC3) was obtained in RJ.

The detailed analysis of regional operating models is provided in section 5.1, while section 5.2 describes the impact assessment of each case study.

5.1. Operation model sustainability

Tables 3–5 show the results of the operation indicators for the three Brazilian states, along with heat maps showing the normalised results. Green represents the best scores, while red indicates the less successful results. Fig. 7 shows the energy consumption and real energy needs of each region's system type, identified during field visits. These systems

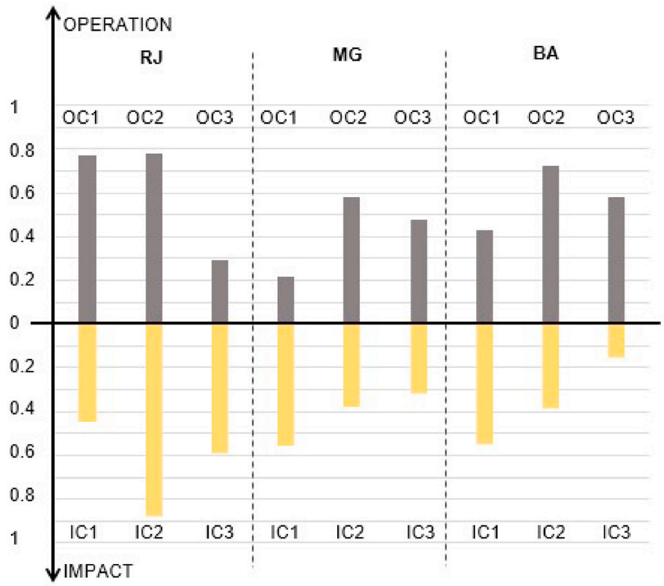


Fig. 6. Operation and Impact result matrix for the three Brazilian states (RJ: Rio de Janeiro; MG: Minas Gerais; BA: Bahia; OC: operation criteria, coloured in grey; IC: impact criteria, coloured in yellow).

include SIGFI80, installed in RJ (RJ-80) and SIGFI13 in MG and BA. All MG functional systems have adaptations made by users, with some retaining more of the initial characteristics (MG-13) and others showing greater changes (MG-OWN). Most of BA's SIGFI13 are still working (BA-13) and some have been improved by users to supply more power (BA13-IMPROVED). The real energy needs have been estimated considering energy consumption and user-reported unmet energy needs.

Comparing regions, the operational status of the systems is uneven. RJ and BA generally have functioning systems, while only a minority are still operating in MG, thanks to beneficiaries' self-maintenance (OI1.1). This disparity influences beneficiaries' perceptions of the program's general quality and execution, with RJ and BA beneficiaries being moderately satisfied and MG beneficiaries expressing more disappointment (OI1.2, OI1.3). Beneficiaries in all regions note that the systems performed better initially but have experienced decreasing energy availability over time (OI1.4). Users also report reduced energy availability during rainy days due to the undersized storage systems (OI1.5). As shown in Fig. 6, users with self-managed systems (BA-13-IMPROVED and MG-OWN) consume more energy than those with the original systems (BA-13, MG-13). RJ displays diversity in energy demand with some maintaining low consumption habits and others exceeding the available capacity, resulting in varying perceptions of program quality.

Maintenance practices also differ among regions due to implementation periods and the systems' operating status. RJ's newly installed systems had not required maintenance at the time of the visit. MG systems have lacked maintenance for over 11 years. BA systems have had an active maintenance plan since their implementation, with an average response time of 105 days (OI1.9). Considering the period with active maintenance practices for MG, all regions employed a corrective maintenance strategy based on user request. While MG and BA users found the quality of maintenance acceptable (OI1.6), they rated its frequency as generally low (OI1.8). From the user's perspective, communication difficulties with the electrification agents were determining factors for troubleshooting delays (OMI1.10, OI1.11). The main complaints encompass inadequate telephone coverage, limited internet connectivity and the difficulty of reaching the maintenance company by phone, which often means travelling to the nearest office. Notably, improved user-agent communication could have mitigated damages caused by robberies and floods in MG. Users in MG and BA expressed disappointment with both the installation and distribution companies,

Table 3
Maintenance plan (OC1) indicators and heat maps for the three study regions, ranging from green (positive result) to red (negative result) (RJ: Rio de Janeiro; MG: Minas Gerais; BA: Bahia; II: impact indicator).

Indicators (I)		Assessment	RJ	MG	BA
OI1.1	General operating condition of the systems	% of working systems	100%	23%	91%
OI1.2	Beneficiaries' satisfaction with the program execution	1 – 5	3	1.8	2.7
OI1.3	Beneficiaries' general satisfaction with the program	1 – 5	3.3	2.2	3.4
OI1.4	Beneficiaries' perception of energy availability	1 – 5	4.3	2.4	2.4
OI1.5	Beneficiaries' perception of energy availability during rainy days	1 – 5	3.3	1.7	1.5
OI1.6	Beneficiaries' perception of maintenance quality	1 – 5	-	2.9	3.7
OI1.7	Presence of protections and circuit breakers in the community	% of communities with protections	100%	27%	73%
OI1.8	Beneficiaries' perception of maintenance frequency	1 – 5	-	1.8	2.1
OI1.9	Average time of service interruption waiting for maintenance according to field reality	Days	-	No maintenance (+11 years)	105
OI1.10	Beneficiaries' perception of the quality of the communication channel with the installation company	1 – 5	4.8	1.7	2
OI1.11	Beneficiaries' perception of the quality of the communication channel with the distribution company	1 – 5	3	1.9	2.4
OI1.12	Potential battery-related socio-environmental risk due to maintenance malpractices and disposal	Actions that can represent a risk (None / Some / No maint)	None	No maintenance	Some

Table 4
Local involvement (OC2) indicators and heat maps for the three study regions, ranging from green (positive result) to red (negative result) (RJ: Rio de Janeiro; MG: Minas Gerais; BA: Bahia; II: impact indicator).

Indicators (I)		Assessment	RJ	MG	BA
OI2.1	Beneficiaries' perception of equity in the program access	1 – 5	2.8	4.9	4.9
OI2.2	Beneficiaries' perception of equity in the capacity installed	1 – 5	5	4.9	5
OI2.3	Beneficiaries considering they received capacitation	% families	100%	23%	61%
OI2.4	Beneficiaries' perception of equity in the capacitation activities	1 – 5	5	5	4.7
OI2.5	Beneficiaries' perception of the quality of the capacitation	1 – 5	4.6	2.7	3.6
OI2.6	Beneficiaries' perception of the intelligibility of the booklet	1 – 5	4.6	3	3.8
OI2.7	Beneficiaries that have succeeded in self-management	% of families	0%	23%	0%
OI2.8	Beneficiaries that still remember what they learned	% of families	100%	33%	94%

Table 5
Tariff (OC3) indicators and heat maps for the three study regions, ranging from green (positive result) to red (negative result) (RJ: Rio de Janeiro; MG: Minas Gerais; BA: Bahia; II: impact indicator).

Indicators (I)		Assessment	RJ	MG	BA
OI3.1	Average energy cost per kWh without discounts	R$/kWh·month	2.39	0.85	0.87
OI3.2	Average energy cost per kWh with discounts	R$/kWh·month	-	0.41	0.24
OI3.3	Additional costs to the bill for administrative reasons	Cost type (R$/month)	Displacement cost (56R$)	Displacement cost (27R$)	Extraction cost (2R$) Displacement cost (33R$)
OI3.4	Beneficiaries' perception of tariff according to the service supplied	1 – 5	2.8	2.7	3
OI3.5	Beneficiaries paying promptly	% of families	100%	20%	90%
OI3.6	Availability of TSE regarding family salary	% of families eligible / % of families receiving	25% / 0%	71% / 18%	86% / 13%

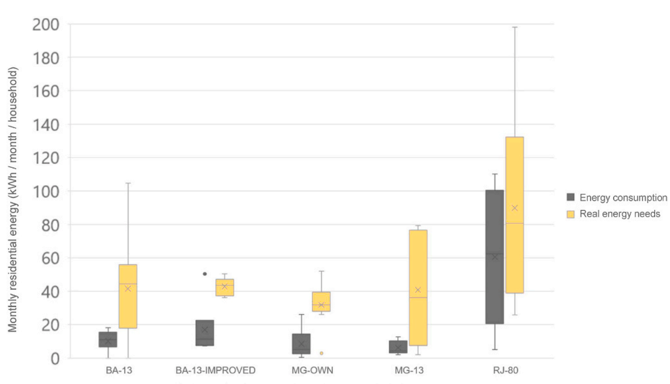


Fig. 7. Monthly residential energy consumption (kWh/month) for each system type (RJ-80: 80 kWh/month systems installed in Rio de Janeiro; MG-13: 13 kWh/month system installed in Minas Gerais; MG-OWN: 13 kWh/month system self-managed by users in Minas Gerais; BA-13: 13 kWh/month system installed in Bahia; BA-13-IMPROVED: 13 kWh/month system improved by users in Bahia).

especially with the former, due to the lack of transparency during the system implementation. Beneficiaries in RJ had a more positive experience with the installation company, DR Energia, thanks to a close and professional relationship.

Moreover, the operational status of the systems can pose social and environmental risks. The majority of systems in RJ and BA, but only few in MG, are equipped with grounding and circuit breakers to prevent accidents related to voltage and current variations (OI1.7). The rest of the systems are therefore exposed to lightning, which has been a notable cause of failure. The heterogeneity of the system's safety in Bahia results from a combination of the lack of technical regulations at the beginning of the program and poor maintenance over the years. Additionally, prolonged delays, insufficient maintenance and inadequate practices can represent a health risk. For instance, in BA, certain users reported that management companies were replacing batteries with used ones, while others detected unusual odours emanating from the batteries, suggesting substandard maintenance of the ventilation system and wiring (OI1.12). In MG, some beneficiaries installed the batteries inside their homes to minimise the risk of robbery, without considering the need for proper safety measures. Paralysed maintenance in MG also contributed to the absence of mechanisms for the disposal of old batteries, resulting in their degradation and environmental pollution. Finally, in both states, user-adapted systems often lack essential safety protections.

In terms of local involvement, mostly positive opinions were collected about the program's equity (OI2.1-OI2.2) and the capacitation results (OI2.3-OI2.8). The vast majority of beneficiaries in the three regions were satisfied with the program's inclusiveness, since it provided systems of equal capacity to most families in the community. The only exception is observed in RJ, where some houses could not benefit from the LpT program due to the lack of an environmental licence (OI2.1). According to the interviews with the electrification entities' representatives and program beneficiaries, training sessions were held during the systems' installation in the beneficiaries' households without any age or gender-based discrimination (IO2.4). Additional group sessions were carried out in RJ, adapted to the communities' cultural characteristics. This training primarily addressed the correct use and operation of the systems to standardise maintenance practices. However, many beneficiaries in MG and some in BA do not recall receiving training (OI2.3). This suggests that either not all the installation companies provided training, or these lacked appropriate format or content. The beneficiary's perception of capacitation quality (OI2.5) and the intelligibility of the training booklet (OI2.6) follow a similar trend. In MG, where quality was rated lower, only a few users who received training still remembered what they had learned. In contrast, initial training is still remembered in BA, where most of the systems continue to work and the training is better rated (OI2.8). The content quality also influences these results. In MG, training mainly focused on the functional use of the systems (i.e., electrical equipment supported). In BA, some households received additional recommendations on solar panel protection and cleaning. Meanwhile, in RJ, beneficiaries received in-depth training on correct and rational energy use, along with instructions on identifying circuit breaker issues. However, most communities lacked important technical information, such as understanding the depth of discharge limit of the battery, indicated by the charge controller.

Finally, the three regions present some differences regarding the energy tariff. In MG and BA the rate is based on a fixed monthly consumption of 13 kWh, with a variable price determined by the concession area (OI3.1). In contrast, RJ systems are equipped with meters and the tariff is proportional to consumption, with a minimum consumption of 30 kWh/month. Consequently, some RJ users who do not reach the minimum consumption quota end up paying a higher rate per kWh compared to MG or BA. To promote energy affordability among low-income families, a social energy tariff (TSE) was introduced as a partial and scaled-up subsidy. This mechanism, although benefitting some families, does not reach all the eligible beneficiaries (OI3.6). The discount received in MG appears to be lower than that received by BA families (OI3.2). Furthermore, the lack of tariff transparency and user-agents communication has led to misunderstandings regarding the scope of discounts and payment methods. In MG, a majority of beneficiaries thought that the systems were completely subsidised, which was a significant reason for accepting them. Some RJ users were unaware of the existence of a minimum rate of 30 kWh/month and felt frustrated at not being able to benefit from the TSE. Beneficiaries were also required to travel to the nearest city monthly and cover their own transportation costs (OI3.3). In some BA municipalities, users are paying the bill extraction cost, which was initially assumed by the distribution company. These administrative and travel expenses notably increase the real cost of the electricity. The majority of beneficiaries found the tariff to be expensive compared to the grid's cost, despite the greater availability limitations and reliability issues of individual systems. This has led to a slight dissatisfaction with the tariff-service relationship (OI3.4). In MG, the low (or inexistent) frequency of maintenance accentuates the rate of non-payments in this region (OI3.5).

5.2. Impact sustainability

Tables 6–8 show the results of the impact indicators for the three Brazilian states, along with heat maps showing the normalised results. Green represents the best scores, while red indicates the less successful results.

Table 6
Psychological development (IC1) indicators and heat maps for the three study regions, ranging from green (positive result) to red (negative result) (RJ: Rio de Janeiro; MG: Minas Gerais; BA: Bahia; II: impact indicator).

Indicators (I)		Assessment	RJ	MG	BA
II1.1	Beneficiaries that mentioned each type of ICTs improvement	% of mentions to smartphones / TV / internet / Radio	25% / 50% / 25% / 0%	44% / 19% / 6% / 25%	45% / 40% / 15% / 0%
II1.2	Phone signal access in the communities	% of communities that gained access during program implementation / latter	50% / 0%	44 % / 33%	16 / 58 %
II1.3	Internet access in the communities	% of communities that gained access during program implementation / latter	50% / 0%	30 / 30%	0 / 53%
II1.4	Beneficiaries' perception of ICTs improvement due to the program	1 – 5	5	3	4.1
II1.5	Main reported energy-related education improvement at school	% of mentions to child nutrition / lighting by day/ lighting at night / TICs access	0% / 0% / 0% / 0%	18% / 45% / 0% / 27%	11% / 42% / 37% / 26%
II1.6	Beneficiaries' perception of education improvement in the school due to the program	1 – 5	-	4.3	3.4
II1.7	Beneficiaries' perception of general education improvement in the community due to the program	1 – 5	-	4	3.6

Table 7
Physical improvement (IC2) indicators and heat maps for the three study regions, ranging from green (positive result) to red (negative result) (RJ: Rio de Janeiro; MG: Minas Gerais; BA: Bahia; II: impact indicator).

Indicators (I)		Assessment	RJ	MG	BA
II2.1	Health-related energy needs covered at household level	Yes / No (% of communities mentioning specific covered/uncovered needs)	Yes (50%)	No (55%)	No (68%)
II2.2	Beneficiaries' perception of energy availability for health needs	1 – 5	5	1.5	1.8
II2.3	Communities with, at least, internal and regular medical assistance	% of communities	40%	55%	21%
II2.4	Reduction of pollution in household lighting due to the program	Average contamination reduction thanks to clean lighting (%)	100%	50%	70%
II2.5	Beneficiaries' perception of contamination reduction due to the program	1 – 5	5	3.8	4.3

Table 8
Socio-economic development (IC3) indicators and heat maps for the three study regions, ranging from green (positive result) to red (negative result) (RJ: Rio de Janeiro; MG: Minas Gerais; BA: Bahia; II: impact indicator).

Indicators (I)		Assessment	RJ	MG	BA
II3.1	Means of supplying the energy needs for productive activities	Only SIGFI / Extra sources (Thermal loads / Generator)	80% / 20% (20% / 0%)	50% / 50% (20% / 40%)	5% / 95% (37% / 79%)
II3.2	Beneficiaries' perception of productivity improvements	1 – 5	4.3	2.6	2.3
II3.3	Beneficiaries' perception of energy availability for productive activities	1 – 5	3.5	1.8	1.9
II3.4	Beneficiaries repressed energy needs	extra kWh/month/household	29.4	25.5	30.3
II3.5	Percentage of beneficiaries needing extra energy to cover their needs	% of beneficiaries	33%	67%	83%

From the perspective of psychological development, beneficiaries perceive improvements in ICT access (II1.4), mainly through the use of television (TV) (in RJ; II1.1) and smartphones (in MG and BA; II1.1). This variation can be attributed to the age demographics in these communities, with RJ having an older population and MG and BA having a younger one. Radio usage is decreasing in all communities, but remains utilised among some MG beneficiaries, since they are more robust technologies in areas with a poor phone signal or energy system operation. Improvements related to smartphones and the internet are uneven, as they depend on internet connectivity, with communities closer to urban areas having 4G mobile data while isolated ones rely on private rural Wi-Fi initiatives (II1.2, II1.3). Users from BA complained about reliability concerns after gaining rural Wi-Fi in their community. Since these ICT require additional energy-consuming devices like routers and modems, the lack of user awareness leads to 24 h running loads, reducing daily energy availability.

Beneficiaries in MG and BA reported medium-high satisfaction with the improvement of children's education, both in school and households, during the program (II1.6, II1.7). MG beneficiaries show higher satisfaction due to a greater number of high-capacity electrified schools. RJ did not have this data due to the lack of operating schools in the visited communities. The beneficiaries recognise enhanced ICT access at school, along with benefits like lighting on dark days and improved children's nutrition through food refrigeration (II1.5). Electricity access, especially night illumination, enabled children to continue learning remotely during the Coronavirus Disease 2019 pandemic, as rural schools stopped in-person activities (from March 2020 to June 2021 in MG and to October 2021 in RJ and BA [68]). It is important to contextualise that before the pandemic, only 56%, 41% and 64% of rural schools were active in RJ, MG and BA respectively, due to a process of rural school centralization [69]. As a result, electrified households are playing a greater role in children's education in isolated communities.

In terms of physical improvements, household electricity has notably reduced pollution, by decreasing the use of diesel oil, kerosene and fires for lighting, which is appreciated by the beneficiaries (II2.4, II2.5). However, due to the lack of maintenance in MG, some beneficiaries had to revert to these fuels, especially on low radiation days. It is worth mentioning that photovoltaic panels have a longer life expectancy than the rest of the system [69], allowing MG users to charge lamps directly from the solar panels during the day, despite the system's deterioration. Many families still use biomass for cooking, but efficient stoves are prevalent, significantly reducing non-clean cooking contamination. When affordable, biomass is replaced by liquefied petroleum gas. The absence of waste collection services leads to waste burning, posing local health and ecosystem risks, often unknown to users.

Regarding health-related energy needs at household level, there are very contrasting perceptions among users. RJ beneficiaries are generally satisfied, but MG and BA systems seem inadequate for addressing health needs (II2.1, II2.2). Users from these two regions primarily require electricity for vaccine refrigeration, especially insulin injections. In RJ, the focus is on first aid and prevention equipment, such as monitoring blood pressure or glucose levels. Other mentioned needs include devices to improve the well-being of chronic patients (i.e., blenders to improve the nutrition of infantile paralysis or stroke patients) and assistive breathing machines (i.e., for asthma patients and neonatal care). When it comes to professional health assistance, a medium (RJ and MG) and low (BA) percentage of the communities receive periodic medical assistance (once or twice a month) (II2.3). However, none of them have continuous healthcare services nor health centre facilities and there is no public transport to the nearest hospital.

The SIGFIs have generated different impacts on the socio-economic development of the visited communities. In RJ, 80% of the beneficiaries have sufficient energy (80 kWh/month) to meet their low-scale productive needs, associated with fish conservation (refrigerators) and small manufacturing (masonry tools) (II3.1) and express reasonable satisfaction (II3.3). It is worth noting that some users in RJ have not yet transitioned to these energy sources and continue to use gas refrigerators. In contrast, in BA, only 5% of users have adequate productive energy access, and satisfaction rates are very low (II3.1, II3.3). In this drought-stricken region, 79% of users require additional generators for tasks like water pumping for crop irrigation and animal feed grinding. A significant percentage of beneficiaries (37%) also use thermal loads, such as wood, for processing fruits and sugar cane byproducts (i.e., rapadura, cachaça) (II3.1). In MG the productive energy needs differ in the two regions visited. The first is devoted to self-sustaining family farming and mining, with ample access to gravity water. The second region focuses on family farming and artisanal fishing and meets its additional agricultural and livestock energy needs (i.e., cassava flour production) with generators and biomass. Although MG inhabitants consider energy access insufficient for their productive demands (II3.3), half are satisfied with the energy provided by their semi-functional PV systems (OI1.1). Users' perception of improved productivity (II3.2) is higher than their perception of productive energy availability (II3.3), highlighting the indirect energy benefits such as increased productive hours due to lighting. A large percentage of people in BA and, to a lesser extent in MG, claimed to require on average 30.3 and 25.5 extra kWh/month, respectively, to meet their basic energy needs (II3.4, II3.5).

6. Discussion

Section 6.1 presents a discussion of the results obtained from the LpT program's operation and impact sustainability assessment and their implications. Then, the main policy recommendations for future last-mile rural electrification initiatives are presented in section 6.2.

6.1. Insights and implications

Table 3 underscores the challenge of dimensioning last-mile electrification systems. Low-capacity systems become obsolete after some operation time, causing energy shortage and user dissatisfaction. In MG and BA, energy limitations lead to technological rejection and all the users preferred unlimited grid access as opposed to PVS. The loose of technological trust is also identified by Hellqvist & Heubaum [27], associated to a lack of PVS standard and reduced energy quality provided. Fig. 7 highlights the dynamic nature of energy demand, which tends to increase over time. After some months of operation in RJ, there was a distinction between users maintaining low consumption habits and those exceeding the available capacity, leading to diverse opinions and affordability issues for low-consuming users. Under- or over-dimensioning generated, in both cases, user dissatisfaction with the service provided, recalling the need for user-centred dimensioning that considers the energy dynamics. According to the World Bank [70], off grid initiatives should consider balancing PVS with possible future grid extension or mini-grid distribution systems in response to the dynamic energy demand and the population growth.

Results from Table 3 emphasise the importance of continuity and quality maintenance practices. A corrective on-demand troubleshooting strategy has proven more effective when coupled with a clear user-agent communications channel. Phone and internet access demonstrate a great potential to facilitate this, contributing to prevent larger issues such as equipment damage during floods or robberies. The usefulness of technological innovations and particularly ICT usage on remote monitoring of system performance, is also highlighted by Elahi et al. [18]. Moreover, there is a tendency to lower the initial maintenance standards and commitments over time, which poses potential risks to users' health and the environment (i.e., battery degradation, lack of safety measures and protection) [27]. Proper regulations and incentives can contribute to ensuring management service quality and continuity [16]. For instance, in Bahia, the regional distribution company, Coelba, adopted PVS as a business strategy, motivating the ongoing activities [50].

As demonstrated by Table 4, inclusive access, system capacities and training were observed in all regions, except for the entry barrier related to environmental licensing in RJ. Proper capacitation and functioning systems are closely related [14]. Low-skilled corrective and preventive maintenance tasks performed by users (i.e., circuit breaker issues, solar panel cleaning) contribute to sustained system operation and enhance people's engagement. The battery discharge limitation is an important concept that should be communicated to users. Most regions visited had inhabitants with technical skills (MG, BA) and present self-organization capacity through community associations, providing a breeding ground for participative systems management.

The results from Table 5 indicate the importance of long-term tariff transparency. Initiatives that start with free or subsidised systems during the initial phase see user dissatisfaction when costs increase. Administrative and travel expenses can notably raise the cost of electricity, posing affordability concerns for low-income families. Furthermore, operation interruptions lead to a higher price paid by users compared to the energy delivered. The case studies reveal a vicious circle: the tendency of tariff increase is coupled with the decrease of system quality and lowering of maintenance standards, which demotivate user payments. Non-payment, in turn, leads to maintenance task interruptions. Transparent tariff mechanisms can reduce non-payment, prevent maintenance task cuts by the distribution companies (MG, BA), and mitigate the accumulation of beneficiaries' debt.

Table 6 underscored the interaction between ICTs and rural electrification. The transition from radios to telephones and internet usage indicates growing confidence in the energy systems and expanding phone and data coverage. The applicability of these disruptive technologies varies depending on internet connectivity type. A smartphone and an energy availability of 13 kWh/month appears suitable for communities with 4G internet access. However, more isolated communities need rural Wi-Fi infrastructure, requiring higher investment and PVS capacities. ICT are also acquiring emerging roles in schools and household education, especially addressing challenges such as rural schools' centralization and pandemics, which have negatively impacted rural students' enrolment [71]. The GIGA initiative is particularly focused on fostering universal access to the internet in schools, recognising the important role of electricity in education [72]. Lighting and IT equipment improve pedagogic quality, support inclusive evening classes and enhance quality activities, improving and broadening educational programs. The results from the field analysis are validated at national level, since statistics [73] show that PV-powered schools in RJ, MG and BA allowed the use of TV, printers, audio systems and computers and illuminate evening classes for youths and adults.

Table 7 identifies the main impacts on health. While SIGFI13 helps reduce indoor pollution, it has limitations in providing healthcare. Similar results are identified by Gogla's report, where from the 104 million people with access off-grid PVS, only 374,000 use water pump and 121,000 refrigeration [8]. Health requirements span households (i.e., patient well-being through household medical equipment or electrical devices) and often inaccessible health centres, requiring travel. An energy availability of 80 kWh/month appears suitable for adequate household-level health assistance. However, health prevention and environmental education are lacking, although the adoption of efficient cookstoves demonstrates the users' interest in adopting healthier practices. The main observed barrier to liquefied petroleum gas adoption is its cost. In line with Troncoso & Soares [74] and Gill-Wiehl et al. [75], promoting clean cooking requires thus tailored affordability measures.

As outlined in Table 8, productive energy demand is linked to energy availability, starting with indirect benefits such as increased working hours due to lighting (SIGFI13) and extending to household equipment such as refrigerators and masonry tools (SIGFI80). Many of these activities are related to agri-food value chain (fishing, family farming, etc.), and as energy resources grow, these activities transition from subsistence to commercial. Water pumping and food blending tools often rely on additional fuel or thermal loads. Productive development appears to be influenced by the installed energy availability, with traditional income-generating activities influenced by cultural customs and the geo-climatic environment, the institutional efforts of local organizations (SASOP, SAJUC in BA) and continuous support from technicians and community agents. It is worth noting another challenging cycle: although the regional LpT initiative in MG and BA brought energy access, it has not completely alleviated energy poverty since energy access remains limited and the constrained socio-economic development does not lead to increased affordability. Similar insights are identified in Philippines [23], where energy access produced uneven business development and subsequently varying impacts on affordability problems among island inhabitants.

The analysis of the LpT's operational factors for sustained system quality (obj1) and its impact on rural empowerment (obj2) provides valuable insights, applicable to broader off-grid electrification programs. This study shows the lessons learned and promising practices to enhance program design, including aspects such as energy availability dimensioning, user satisfaction, effective troubleshooting practices and the tariff transparency, which are common challenges in last-mile electrification. However, regional variations among case studies underscore how different actors and enabling environments can lead to nuanced outcomes. It is worth noting that while the evaluation criteria considered in this work can be applied to other contexts, their relative importance may vary from one region to another. For instance, the existence of PVS value chains in regional and national markets, which was not a focus in this study due to its similar level throughout the case studies, can be a significant constraint for effective replacements, disposal and recycling in other countries [14,17].

The sustainability impact derived from the LpT analysis has prompted discussions on the benefits and limitations of various energy access levels regarding physical, psychological and socio-economic development. These aspects are context-specific and largely depend on the presence of community services such as schools, health centres and local organizations that promote productive development. Furthermore, these implications are closely linked to the specific technology considered (stand-alone PVS) and different results may arise for other technologies (i.e., wind turbines) or configurations (microgrids). However, the insights gained from analysing different power system levels and their implication for the population offer meaningful guidance for future initiatives. For instance, as SDG7 aims to achieve universal energy coverage by 2030, mainly through low-capacity systems [8], this work recognises that higher-capacity systems could have more significant impacts on rural empowerment.

The study is based on data-driven ad-hoc indicators, which, although comprehensive and of demonstrated validity, may fall short capturing all relevant aspects when applied to different countries and populations or when used to assess rural electrification initiatives based on varying energy technologies, configurations or generation capacities. Furthermore, the methodology considered in this work relies on population samples. While the results provide evidence, further research should complement these findings by considering larger and more diverse samples, as well as seeking disaggregated data related to variables such as gender, age, socio-economic profile and ethnicity.

6.2. Recommendations

This section presents the main recommendations derived from the work's findings and implications, aiming to guide last-mile rural electrification promoters, energy market bodies and policymakers in ensuring sustainable operation and impact within future initiatives.

More concretely, to ensure sustainable access to quality energy (obj1), off-grid energy access initiatives should.

- Dimension energy systems according to user needs. Since energy needs are dynamic and user-specific, depending on factors such as age, purchasing power and gender, people-centred energy audits are recommended during the design phase.
- Include capacity expansion strategies in the maintenance plan. Leveraging the modularity of PVS, capacity expansion should be considered upon users' request (as suggested in the LpT manuals).
- Standardise and regulate maintenance procedures that include a disposal policy and rigorous equipment condition checks (i.e., grounding, ventilation systems).
- Implement effective communication channels, based on local availability, and ensure clear and timely communications with users about any changes in maintenance procedures (i.e., changes in maintenance companies).
- Guarantee allocation of maintenance costs within the program budget and provide incentives to distribution companies to ensure their long-term commitment.
- Ensure off-grid energy tariffs' fairness compared with on-grid. Availability and reliability limitations of off-grid systems should be compensated to avoid users' technological rejection and distrust (i.e., discounts for energy interruptions caused by maintenance delays).
- Tailor payment mechanisms to users' preferences, by exploring negotiations on the frequency and form of payment (i.e., trimestral face-to-face payments, online payments).
- Encourage community engagement and participatory management models through more comprehensive and frequent community training, covering energy efficiency measures, operation and low-skilled corrective and preventive maintenance tasks.

To enhance people's empowerment (obj2), off-grid energy access initiatives should.

- Promote phone coverage and internet connectivity (4G or rural Wi-Fi antenna) to improve ICT access and troubleshooting mechanisms.
- Align with community educational services to strengthen their resilience and offer quality pedagogic content and formats through access to internet and audio-visual equipment.
- Strengthen community health through equipping electricity-related healthcare infrastructure for prevention, patient well-being and disease treatment.
- Ensure clean indoor environments by complementing rural electrification initiatives with solar lantern distribution, strengthening clean cooking mechanisms and the deployment of environmental education practices.
- Enhance multi-stakeholder collaboration between rural electrification promoters and local organizations to maximise rural empowerment and support the development of sustainable productive

activities. Guarantee permanent productive advice for the electrified communities.

- Address dynamic energy needs and plan for developing productive energy requirements (i.e., from extended working hours, subsistence food production, increased monetised production and diversification of productive activities).
- Integrate the energy-water-food nexus in electrification project dimensioning and energy application planning. As family farming is a mainstay of many rural last-mile communities, access to food refrigeration and water are determining factors for food security and productive development.
- Foster local consumer advocacy by encouraging the establishment of local bodies that advocate for the rights of last-mile consumers in rural electrification programs. These bodies should aim to build negotiating power with rural electrification actors and cultivate a trust-based relationship with the beneficiaries.

7. Conclusions

This work presents a comprehensive assessment of the long-term sustainability of a world-wide referral in terms of rural electrification, the Luz para Todos (LpT) program in Brazil. In particular, photovoltaic solar systems (PVS) applied to last-mile rural electrification have been analysed within the framework of two design objectives: the durability of quality energy access (obj1) and achieving the rural population's empowerment through energy access (obj2).

The results reveal a varied landscape of LPT program operation and impact across the different Brazilian study regions. High-capacity electrification has been achieved post-2020 for a limited audience in RJ, an incomplete and semi-abandoned pre-electrification policy characterise MG, and BA has seen extensive but low-capacity rural electrification. These complementary experiences offer meaningful lessons learned into operation and impact sustainability, leading to a set of recommendations for research, rural electrification promoters, and policy makers.

Engineering design should dimension energy needs based on people-centred audits and incorporate capacity expansion strategies within maintenance plans. In term of regulations and policies, standardised and regulated maintenance practices, budgets allocation, quality standards, disposal activities, and user-agent communication channels are required, ensuring favourable impact on environmental, social and governance aspects. Regulations should guarantee frequent and in-depth community training, fundamental for long-term project survival and beneficiaries energy governance and skills development. To ensure energy tariff fairness and affordability, regulatory mechanisms should consider and compensating for higher duration of energy interruptions and additional user displacement costs due to PVS remoteness. Rural electrification can foster empowerment and align with United Nations Sustainable Development Goals (SDGs), but requires further actions. Sustainable access to education calls for both equipped centres (office supplies, audio-visual pedagogic material and food safety electrical appliances) and institutional alignment, particularly in light of the Coronavirus Disease 2019 recovery and the trend of rural school centralization. Physical improvements require medical infrastructure, electrical equipment and personnel (for prevention, treatment and patient comfort), community sanitation services, clean appliances for lighting and cooking, and environmental education. Food refrigeration and water access are both essential for guaranteeing food security and establishing the development of income-generating activities, especially in communities with family farming. Smartphones and the internet have a great local empowerment potential if internet and phone connectivity and coverage and the additional required energy capacity are considered in the system's design and promoted by the initiative. Lastly, full socioeconomic development can be achieved by addressing these energy needs through PVS with greater capacities adapted to productive demand and the support of local organizations that promote sustainable and inclusive income-generating activities.

This collection of long-term practical experiences aims to guide rural electrification policies and last-mile interventions to effectively address both the durability of PVS-based projects and the drivers to strengthen local rural empowerment. This analysis highlights the necessity for further research in several areas. Future bottom-up analyses should delve deeper into the nuanced outcomes observed across regions, technologies and targeted population groups. In particular, inclusive and gender-responsive initiatives demand more attention and investigation. This knowledge will help tailor and operationalise future initiatives, considering these specificities. The pressing concern about the sustainability of off-grid electrification necessitates the integration of these long-term experiences and practical knowledge into a global framework to guide strategic actions. Exploring the real-world implications of different power capacities to meet SDGs requires further attention to prioritise synergic initiatives addressing multiple goals.

CRediT authorship contribution statement

A. Leduchowicz-Municio: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization, Project administration. **M. Juanpera:** Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration. **B. Domenech:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision, Project administration. **L. Ferrer-Martí:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition. **M.E.M. Udaeta:** Resources, Supervision. **A.L.V. Gimenes:** Resources, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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APPENDICES.

Appendix A – Criteria and Indicators selection

Type	Criteria	Indicators	References
Operation	OC1. Maintenance plan	Energy sufficiency and quality (energy availability, reliability, energy per capita, energy security); maintenance (type, quality and frequency); communication with beneficiaries; disposal strategy	[13–15,24,25,28,29,58–60]
	OC2. Local involvement	Capacitation of beneficiaries, local participation in maintenance or management activities, development of O&M skills, equity in program access.	[15,24,28,58–60]
	OC3. Tariff	Electricity tariff, ability to pay for the tariff, satisfaction with tariff, social assistance mechanisms, tariff fairness	[14,15,24,28,29,58–60,62]
Impact	IC1. Psychological development	Information and communication technologies and services, education services	[15,24,60–62]
	IC2. Physical improvement	Health service improvements, safety, contamination reduction, deforestation reduction, impact on ecosystem	[15,23,24,28,29,55,59,60,62]
	IC3. Socio-economic development	Development of productive activities, job opportunities, community organization, poverty alleviation	[15,23,24,28,29,55,58–60,62]

Appendix B – Semi-structured interviews

1- General community data

- Date, state, municipality, community
- Interviewee: name, age, gender, profession, community role
- Ethnicity/cultural identity, number of families, age and gender distribution, social organization, community existence duration

2- General system data

- Table of all community electrical generation systems: load type, units served, technology used, capacity (kwh/month), energy resource, installation year, application, concession area, executing agent, involved NGO/association, universalization program, operational state
- Service request date, person requesting service, installation date, duration of works

3- Technical data of the systems

- System type and capacity:
  - Solar panels: units, power (Wp), brand/model
  - Batteries: units, power (Ah), brand/model
  - Inverters: units, power (VA/W), brand/model
  - Controllers: units, power (A), brand/model
  - Generator: units, power (VA), brand/model
- Local adaptations, protection against atmospheric discharges, consumption meter, site illumination, perimeter protection
- Existence of grid, electricity pole conditions, distribution voltage (kV), public lighting pole conditions, distribution voltage (V)

4- Program operation data

4.1- Availability and reliability.

- Number and frequency of recorded power interruptions
- Energy availability and limiting consumption mechanisms
- Requests for system capacity expansion, system combinations, and community-purchased equipment

4.2- Maintenance.

- Existence, frequency, and executor of maintenance plans
- On-site operation and maintenance manuals, availability of spare parts/tools

4.3- Failure and disposal.

- Failures, part replacements, common problems, cost responsibility, and technician response time
- System parts disposal management, type, frequency, and executor

4.4- Tariffs.

- Paid fee details, fee type, price range, discount details, and installed system cost (R$/Kit)

4.5- Trainings.

- Training content, frequency, local adaptation, community-wide coverage
- Delivery of a guidance booklet, language, and content
- Community participation an involvement in maintenance, and local presence of workers

4.6- Communication channels.

- Community-contractor and community-distributor communication channels
- Channels for complaints and emergencies

5- Program impact data

5.1- Basic services.

- Availability before and after LpT: Electric power, water, basic sanitation, waste disposal

5.2- Communication.

- Availability before and after LpT: Telephone signal, 4G network, access roads

5.3- Education.

- Presence of a school, electricity before and after LpT, new electrical equipment

5.4- Health.

- Presence of a health post, electricity before and after LpT, new electrical equipment, health-related needs
- Practices before and after LpT: Fires, kerosene, candles

5.5- Productive activities.

- Productive activities, energy sources before and after LpT, government aid, community income range

5.6- Environmental impact.

- Vegetation and access road management around systems

Appendix C – Structured interviews

1- Contact information

- Day (open-ended)
- State (open-ended)
- Municipality (open-ended)
- Community (open-ended)
- Ethnicity/Cultural group (open-ended)
- Role in the community (open-ended)
- Name (open-ended)
- Age (open-ended)
- Gender (multiple choice - open-ended: Female/Male/Other)

- Occupation (open-ended)
- Highest education level (multiple choice - open-ended: Did not attend school/Elementary school/High school/College/Other)
- Average monthly family income (multiple choice - open-ended: Less than half the minimum wage/Between half and 1 minimum wage/Between 1 and 3 minimum wages/More than 3 minimum wages/Other)
- Government social programs (multiple choice - open-ended: Bolsa Família/Retirement/COVID Emergency Aid/Other)
- Type of energy before the LpT program (multiple choice - open-ended: No electricity/Distributor's grid/Informal grid connection/Solar energy/Generator/Other)
- Type of energy after the LpT program (multiple choice - open-ended: No electricity/Distributor's grid/Informal grid connection/Solar energy/Generator/Other)
- System type (multiple choice: SIGFI – stand-alone PVS/MIGDI - microgrid)
- System capacity (open-ended)

2- Consumption profile

- Electrical equipment acquired at home after the LpT program (multiple choice - open-ended: Television/Satellite dish/Mobile phone/Computer/Radio/Wi-Fi router/Fan/Refrigerator/Freezer/Sandwich maker/Blender/Washing machine/Electric shower/Hair dryer/Hair straightener/Lamps/Microwave/Other)
- For each electrical equipment:
  Equipment power (W) (open-ended)
  Usage time (hour/day) (open-ended)
  Do not use due to lack of energy (Yes/No)
- Average energy consumption appearing in energy bills (open-ended)

3- System operation

3.1- Availability and reliability.

- How satisfied are you with energy availability for everyday equipment use? (Likert scale)
- How satisfied are you with energy availability on rainy days? (Likert scale)
- How satisfied are you with daily energy reliability? (Likert scale)

3.2- Maintenance.

- Has any maintenance been done on your home's energy system? (Yes/No)
- How satisfied are you with the quality of maintenance? (Likert scale)
- How satisfied are you with the frequency of maintenance? (Likert scale)
- Does maintenance include managing vegetation around the system? (Yes/No)

3.3- Failures and disposal.

- Have you experienced problems with the energy system? (Yes/No)
- What are the most common problems? (Multiple choice - open-ended: Battery failure/Inverter failure/Circuit breaker issues/Photovoltaic panel problems/Thefts and burglaries/Corrosion/Lightning strikes/Issues with the internal installation kit/Power outage/Other)
- How do you rate the response time for issue resolution? (Likert Scale)
- Is broken equipment taken away during maintenance? (Yes/No)
- If not, is there someone in the community responsible for disposal? (Yes/No)

3.4- Tariff.

- Do you pay a fee for the energy you receive? (Yes/No)
- What is the fee amount? (Open-ended)
- Do you receive any tariff discounts? (Multiple choice - open-ended: No discounts/Social energy tariff/Other)

- How do you rate the fairness of the tariff in relation to the service provided? (Likert scale)
- Have you paid additional costs beyond the tariff for system operation? (Yes/No)

3.5- Training.

- Did you receive any training during system installation? (Yes/No)
- How do you rate the effectiveness of the training? (Likert scale)
- Do you remember what you learned? (Yes/No)
- Was a booklet distributed to your family? (Yes/No)
- Do you still have the booklet? (Yes/No)
- How do you rate the effectiveness of the booklet? (Likert scale)

3.6- Communication channels.

- How do you rate the communication channel with the company that installed the systems? (Likert scale)
- How do you rate the communication channel with the energy distributor? (Likert scale)

3.7- Implementation Time.

- How do you rate the time it took for the LpT program to reach your home? (Likert scale)
- How do you rate the duration of the construction works? (Likert scale)

3.8 Satisfaction.

- How satisfied are you with the LpT program? (Likert scale)
- How satisfied are you with the company that installed the energy? (Likert scale)
- How satisfied are you with the energy distributor? (Likert scale)

3.9- Ease and safety.

- How do you rate the ease of operating the systems? (Likert scale)
- How safe do you feel operating the systems? (Likert scale)

4- Impact

4.1- Communication and information.

- Which of the following has improved due to the arrival of energy? (Multiple choice - open-ended: Community access roads/Cell phone network/Internet access/Information access via television/Other)
- How do you rate these improvements? (Likert scale)

4.2- Education.

- Have you studied or are you studying at your community school? (Yes/No)
- How do you rate the improvement in the quality of education due to electricity, after the LpT program? (Likert Scale)
- In which areas have you seen improvements? (Multiple choice - open-ended: Able to study more at night due to home lighting/Saved time in daily life, using it to study/Participated in online courses/Participated in more educational activities in the community/Other)
- How do you rate these improvements? (Likert scale)

4.3- Health.

- How do you rate the improvement in the quality of health centre services due to electricity, after the LpT program? (Likert scale)
- Does anyone in your family need electricity for health reasons? (Yes/No)
- If yes, what equipment is used? (Multiple choice - open-ended: Refrigeration of vaccines and medicines (such as insulin for diabetes)/Vital parameter monitors/Dialysis equipment/Mechanical ventilation equipment/Portable oxygen concentrators/Other)
- How do you rate energy availability for these health-related needs? (Likert scale)
- What practices were common in your home before the LpT program? (Multiple choice - open-ended: Burning of waste/Burning of wood or coal for cooking/Use of kerosene for lighting/Use of candles for lighting/Use of bonfires for lighting/Other)
- What practices were common in your home after the LpT program? (Multiple choice - open-ended: Burning of waste/Burning of wood or coal for cooking/Use of kerosene for lighting/Use of candles for lighting/Use of bonfires for lighting/Other)
- How do you rate the reduction of indoor contamination due to solar energy after the LpT program? (Likert scale)
- Which improvements in cooking do you attribute to electricity? (Multiple choice - open-ended: Cook less often due to having a refrigerator to preserve food/Changed consumption habits for healthier food thanks to electricity/Saved time cooking with a blender/Saved time cooking with a sandwich maker/Saved time cooking with a microwave/Other)
- How do you rate these improvements in cooking? (Likert scale)

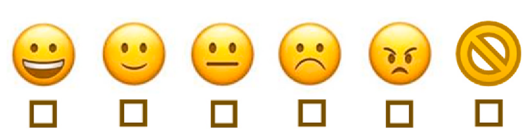
4.4- Productive activities.

- How do you rate the improvements in your work productivity due to electricity after the LpT program? (Likert scale)
- Are you engaging in new productive activities thanks to electricity? (Yes/No)
- If yes, what activities? (Multiple choice - open-ended: Fish preservation/Assisting tourism/Commercial activities/Artisanal activities/Other)
- How satisfied are you with the energy availability to work in your community? (Likert scale)

4.5- Equality.

- In your community, how do you rate the degree of equality in access to the program? (Likert scale)
- How do you rate the degree of equality in receiving the same amount of energy? (Likert scale)
- How do you rate the degree of equality in receiving the same training without discrimination based on gender or age? (Likert scale)

Likert Scale: Which image better captures your feelings, sensations and satisfactions?



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