Energy Policy 167 (2022) 113080

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Last-mile rural electrification: Lessons learned from universalization programs in Brazil and Venezuela

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A R T I C L E I N F O

Keywords:
Rural electrification programs
Emerging economies
Remote energy access
Sustainability
Multi-criteria assessment
Renewable energy

A B S T R A C T

Many countries are still facing a common hurdle: last-mile rural electrification. Great skill is required to face this challenge, which generally involves the most isolated, inaccessible and complex regions. Many Latin American countries have already undertaken universal access to energy schemes and have built an experience base that, if shared, can add a wealth of knowledge to facilitate the implementation of future initiatives. In this regard, this work evaluates the sustainability of the main electrification initiatives developed in Brazil and Venezuela, by performing an ex-post comparative multicriteria evaluation on 18 quantitative and qualitative social, institutional, economic, technical and managerial indicators. Eight discussion threads are drawn from the programs' design and implementation strategies and outcomes. The main insights are: the suitability of renewable-based distributed energy resources for covering last-mile rural electrification; the effectiveness of a private context for the development of the technological market and the creation of policy instruments; and the effectiveness of a public context to implement a greater diversity of technological solutions focused on improving social well-being. The lessons learned aim to guide rural electrification promoters and decision makers in developing more sustainable and successful last-mile electrification initiatives.

1. Introduction

Of the world's population, 9.9% doesn't have access to electricity, equivalent to more than the entire population of Europe; 34% still cooks with polluting technologies and only 17.1% of global energy consumption comes from renewable energy (IEA et al., 2019). Thus, universal, reliable, modern and affordable energy access remains a global challenge, especially in rural areas of developing countries. Numerous rural electrification initiatives are being promoted worldwide, mainly through conventional grid extension. However, in recent years there is an increasing tendency to install decentralised systems (United Nations, 2018), based either on diesel, renewable energies or a combination of both. In fact, it is estimated that, by 2030, 60% of new connections will be generated through clean energies, with autonomous and microgrid configurations representing a high portion of these implementations (IRENA, 2019).

However, these efforts are not enough. The net increase in people with access to energy is hindered by global population growth. Consequently, international agencies estimate that there will still be close to 700 million people without access by 2030. The sustainability of rural electrification operations is also being questioned (IEA et al., 2018). Although more than 140 million people have benefited from autonomous photovoltaic systems in recent years, only 21% of these connections have actually solved the lack of access to energy (IEA et al., 2018). Real energy affordability is a privilege of only 43% of the electrified residences in countries that are achieving universal energy access (IEA et al., 2018). In that sense, the rise in off-grid solar schemes is making it increasingly difficult to accurately analyse trends in rural electrification. Numerous authors and international institutions consider the need to develop more energy forecast methodologies, statistical collection of the most significant data and more evaluations of existing rural electrification schemes (IEA et al., 2018). These specific actions must be carried

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https://doi.org/10.1016/j.enpol.2022.113080
Received 10 February 2022; Received in revised form 5 May 2022; Accepted 22 May 2022
Available online 5 June 2022

out by Governments and distribution companies to ensure sustainable universal energy access (DSDG-UNDESA, 2018; IEA et al., 2018).

Evaluating rural electrification schemes is therefore a necessity to ensure real and sustainable access to energy. There are numerous studies into small rural electrification projects around the world, mostly focused on evaluating specific aspects; but evaluations of entire programs, applied to southern countries using renewable energy, are scarcer. In that sense, the techno-economic analysis of Moner-Girona et al. (2019) creates a spatial model of rural electrification in Kenya, aiming to seek the technological least-cost option. They compare the results with the 2009 rural electrification master plan, highlighting its main limitations and indicating improvements in its design. Hidayah and Rarasati (2020) review the influence of stakeholder management on the sustainability of various rural electrification initiatives. After a literature review, they discuss various classifications of stakeholders, highlight their influence on electrification projects, and defend the relationship between local participation and the sustainability of the initiatives. The evaluation of the socioeconomic benefits of rural electrification programs, based on the statistical analysis of several samples from different periods, is also a subject of study. Fujii and Shonchoy (2020) analyse the relationship between access to energy and reduced fertility in Bangladesh, and identify the use of communication technologies such as television as a relevant causal channel. Adusah-Poku and Takeuchi (2019) evaluate the impact of a rural electrification program applied in Ghana on the variation in the electrification rate and in the well-being of the community, considering the purchasing power of households and the percentage of poor households per community as metrics. Similarly, Kumar & Rauniyar (2018) analyse the benefits of two rural electrification programs implemented in the Kingdom of Bhutan, highlighting the positive impacts on off-farm income generation, improving school time and home education. Monyei et al. (2018) and Kumar (2020) explore the socio-institutional and socio-economic concepts of energy justice and energy poverty, respectively. The former compares a public policy of universal access to off-grid energy with a domestic grid-connected electrification policy applied in South Africa. Benchmarking allows them to identify procedural and distributional injustices, as well as unfairness in meeting the special needs of some population groups. The latter explores the context dependency of energy poverty using a theoretical framework that combines traditional and contemporary assessment models and practical evaluations in 6 rural villages in India. The paper discusses the relationship between rural consumer behaviour and needs, and geographic location, sociocultural traditions and local politics.

Under a different perspective, multicriteria methods are gaining interest among evaluators of rural electrification initiatives. Stritzke et al. (2021) present a method to assess the governance of energy access in the developing world. Based on the literature review and stakeholder interviews, they quantify six institutional indicators to evaluate the quality of current governance for off-grid technology insertion in case studies in Zambia and Uganda. In recent years, the multidimensional perspective is attracting interest in sustainability assessment of energy initiatives. The habit of evaluating techno-economic aspects can be commonly observed, as well as the growing tendency to include social, environmental, institutional and management aspects. Juanpera et al. (2020) develop a 5-dimensional two-phase procedure to assist in the technological design of sustainable rural electrification systems of 26 communities in Nigeria. Their results allow generating an ex-ante and intermediate evaluation of the current national rural electrification plan. Gafa and Egbendewe (2021) focus on the energy poverty concern in rural Senegal and Togo. They identify the national levels of energy poverty using unidimensional and multidimensional analyses, and discuss the causal relationship within socioeconomic criteria and from a gender perspective. Lillo et al. (2021) evaluates 5 different management models applied in isolated small-scale renewable energy projects in Peru, Ecuador and Bolivia. Through a multidimensional analysis, they draw the strengths and weaknesses of each managerial strategy. While some scholars discuss specific elements of rural electrification projects, others develop a general evaluation of the sustainability of energy initiatives. Lestari et al. (2018) analyse 6 autonomous renewable-based systems applied in rural Indonesia, through technical, economic, social, environmental and institutional indicators. The study evaluates each system's sustainability and discusses the causes of its durability. On a broader scale, Gómez-Hernández et al. (2019) conduct an evaluation of 3 rural electrification plans applied in Mexico, considering global characteristics at regional scale, technical specifications at local scale and the system management strategy.

The analysis of the state-of-the-art reveals two groups of studies. The first deals with evaluations of programs and policies at the national level. In these works, different scales of analysis can be identified, including evaluations of the design strategies and the governance contexts where the programs are carried out, analyses of the implementation and management strategies applied, and discussions on the main socioeconomic results of the energy initiatives. All these levels of analysis allow building a picture of the sustainability of rural electrification plans, but none of them presents combined analyses of the three scales. The second group of studies uses multi-criteria approach to analyse the sustainability of specific or more general aspects of energy initiatives. In addition, the reviewed works highlight the relevance of all the technical, economic, social, environmental, institutional and management dimensions to assess the sustainability of rural electrification initiatives. However, a limited number of evaluations simultaneously address large-scale rural electrification initiatives and consider a multi-criteria and multi-dimensional perspective of sustainability. Furthermore, evaluations of major rural electrification programs in the South are scarce and very few studies specifically address the last-mile of rural electrification, despite being a common challenge in these regions. Additionally, to understand the sustainability and durability of rural electrification programs in the most isolated communities, it is essential to develop long-term ex-post quantitative and qualitative evaluations after implementing rural electrification plans (Trotter et al., 2017). According to Winther (2015), more emphasis should be placed on the context in which energy initiatives take place and to the prospects envisioned. The comparison of different rural strategies can help identify the successes and failures of previous initiatives, extrapolate these solutions to other contexts and boost levers of progress towards sustainability in future rural electrification programs.

The present work aims to fill the gap between the current lack of durability of most rural electrification interventions and the scarcity of ex-post and long-term evaluations of energy access programs implemented at national scale. More specifically, the purpose of this article is to evaluate the sustainability of universalization programs applied to the last-mile of rural electrification, based on decentralised systems powered by renewable sources. For that end, we carried out a case-based comparative analysis of the strategies applied in two of the largest last-mile rural electrification programs applied in South America: the "Luz para Todos" (LPT) universalization program applied in Brazil and the "Sembrando Luz" (SL) program in Venezuela. These two countries, are currently at a similar level of rural electrification index, have developed universal energy access programs on similar periods, addressing similar target populations and specially focusing on indigenous communities. Besides, the two programs applied decentralised renewable technologies based on similar natural resources. In both cases, these initiatives have been promoted and coordinated largely or entirely in a centralised manner by the government. As the purpose of this work is to understand the elements that determine the success or failure of last-mile rural electrification initiatives, the two case studies can be considered comparable. The interpretations resulting from the case-based comparative analysis are presented in the form of lessons learned. Qualitative and quantitative data is gathered from several official sources and validated through experts and academics. The usefulness of an analysis based on mixed data, validated by experts, has been demonstrated in literature review as an effective mechanism to extract enriching conclusions for future initiatives (Gómez-Hernández et al.,2019) (Juanpera et al., 2020).

The comparative ex-post assessment of both last-mile rural electrification programs has been carried out with a particular innovation: eight main areas (called discussion threads) have been considered to draw on the lessons learned from both countries' experiences. The contribution to the national rural electrification coverage (D1); the beneficiaries' selection strategy (D2); the energy sovereignty development (D3); the legal and institutional framework development (D4); the management model (D5); the economic model (D6); the technical strategy (D7) and the socioeconomic benefits (D8) have been assessed. Consequently, the most representative aspects of the two electrification programs has been analysed regarding 18 ad-hoc indicators from the institutional, technical, economic, social and management criteria. These indicators have been selected considering previous works and their relevance value according to experts from both rural electrification programs. In addition, all of them satisfy the five indicator selection principles (systemic, consistent with the analysis, independent, measurable and comparable). Results show the suitability of decentralised renewable-based energy systems for the last-mile electrification. However, more energy availability is needed to promote rural socioeconomic development. Private and competitive management resulted in a helpful tool for developing policy instruments and the off-grid energy market, while public interventions with participatory management tended to strive more for energy equity and strengthen local energy sovereignty. These contributions are expected to guide future promoters of rural electrification in building sustainable programs that guarantee lasting access to energy.

The work is structured as follows. First, a description of the rural electrification context of the two countries under evaluation, followed by the main characteristics of the two universalization programs (Section 2). Then, the methodology used and the justification of the chosen analysis structure are explained in detail (Section 3). The following section (Section 4) shows the results of each indicator analysed. Next, the main discussions are presented (Section 5). The last section encompasses the principal conclusions of the work (Section 6).

2. Program descriptions

This section presents the electrification process of the most remote and disperse populations realised by two national universalization programs: the Brazilian "*Luz para Todos*" (LPT) initiative and the Venezuelan "Sembrando Luz" (SL) program. Both countries' rural electrification history is first contextualised, then each program's principal characteristics, from an institutional, technological, social, economic and management perspective, are described.

2.1. Brazil

2.1.1. Rural electrification context

The Brazilian electrical energy system encompasses two main structures. Most of the territory is served by a centralised grid called Interconnected National System (SIN). Due to the ecosystemic fragility of the Amazon rainforest, the northwest is powered by decentralised energy systems called Isolated Systems (SISOL). SISOL account for only 3,4% of the total national installed capacity and are mainly fuel-based grids. The wide rural-urban energy access gap encouraged the development of two main rural electrification programs: "PRODEEM" in 1994, aiming to bring renewable energy to isolated communities and "Luz no Campo" in 1999, consisting of national grid extension through an innovative low-cost technology (Pagliardi et al., 2020). Apart from these initiatives, approximately 30% of rural households were still living without electricity (ANEEL, 2002). In 2002, the Law 10438 defined access to public electrical energy service as a right under the competence of the State, drawing a new path to universalization. In 2003, the LPT program was launched with an initial target of 2 million low-income families (MME-LPT, 2007), expecting to reach 95% of rural electrification coverage by 2008 (ANEEL, 2012a). In 2004, the PROINFA program started, incentivizing the utilization of alternative energy generation sources and completing 1.8% of the total Brazilian installed generation capacity in 2018. The same year, more than 16.3 million people benefited from the LPT program, mainly through national grid extension. However, the initiative exceeded the initial participation expectations, postponing universalization deadlines to 2022 through five program extensions (MME-LPT, 2013a). Nowadays, 1 million people in the most isolated areas of the Amazon region are still without energy access and a new program was initiated in June 2020, the "Mais Luz na Amazonia" (MLA) program (MME, 2020).

2.1.2. "Luz Para Todos" program in the remote regions

In contrast to the majority of LPT's grid extension beneficiaries, assistance was unviable in the most remote isolated, sparsely populated and environmentally sensitive regions. Thus, a new clean strategy based on Decentralised Energy Resources (DER) was considered within the LPT program. The first guidelines appeared in 2009 (MME-LPT, 2009), including all renewable power technologies, but during the 2011–2014 phase two important alternatives based on PV-solar energy came to fruition: the Individual Generation System powered by Intermittent Energy Sources (SIGFI, *Sistemas de Geração com Fontes Intermitentes*) and Isolated Microsystems for Electrical Energy Generation and Distribution (MIGDI, *Microsistema isolados de Geração e Distribuição de energia elétrica*) (ANEEL, 2012b) (MME-LPT, 2015a; 2017a). SIGFI and MIGDI aim to guarantee the use of lighting, cooling and communication devices for residential, community and commercial applications (ANEEL, 2012a). Therefore, a minimum autonomy of 48h and an interruption threshold of 216 h/month and 648 h/year is defined for both technologies (ANEEL, 2012b). The monthly energy availability was initially framed between 13 and 80 kWh per Consumption Unit (CU), but has been increased since 2015 to 45 kWh/month/CU, to guarantee the possibility of refrigeration (MME-LPT, 2015b). Adequate justification is needed for installing more generation capacity. MIGDI implementation is recommended for demands above 900 kWh/month (MME-LPT, 2015a) and limited to capacities up to 100 kW (ANEEL, 2012b).

The program institutional structure is based on a multi-agent model combining public and private organizations (Fig. 1). The Ministry of Mines and Energy (MME) is the program coordinator and has the final decision in project approval (IEMA, 2018). A National (NMC) and a Regional (RMC) Management Committee, formed by representatives of the MME, regulation agencies, electrical concessionaires, state governments and majors, support the MME in determining the priority communities (IEMA, 2018). All the energy distribution activities are regulated by the National Electrical Energy Agency (ANEEL) (MME-LPT, 2013b; 2015a; 2017a). ANEEL establishes the O&M tariff threshold, supervises the commissioning protocol submission (ANEEL, 2012b) and audits the system performance reports (ANEEL, 2008b, 2016). The mixed-economic and state-owned company ELETROBRAS, responsible for the whole program operationalization, evaluates pre-project techno-economic viability (IEMA, 2018), approves the funding release and performs commissioning inspection. The program's execution lies in the hands of the Regional Utility Concessionaire (RUC), which encompasses private distribution companies and rural electrification cooperatives and is responsible for collecting and systematizing all the regional connection demands in its concession. The RUC assumes all project executions and O&M functions, being able to externalise some tasks to local companies.

The LPT program pursues the sustainable development of rural areas by providing energy access and enabling income generation activities (IICA, 2011). Initially, the focus was to assist those houses and institutions (MME-LPT, 2007) from municipalities with lower HDI and electrification rates or affected by hydroelectric dams (IICA, 2011). During the program extensions, the scope broadened to include the connection of schools and health centres. The RUC assume the execution

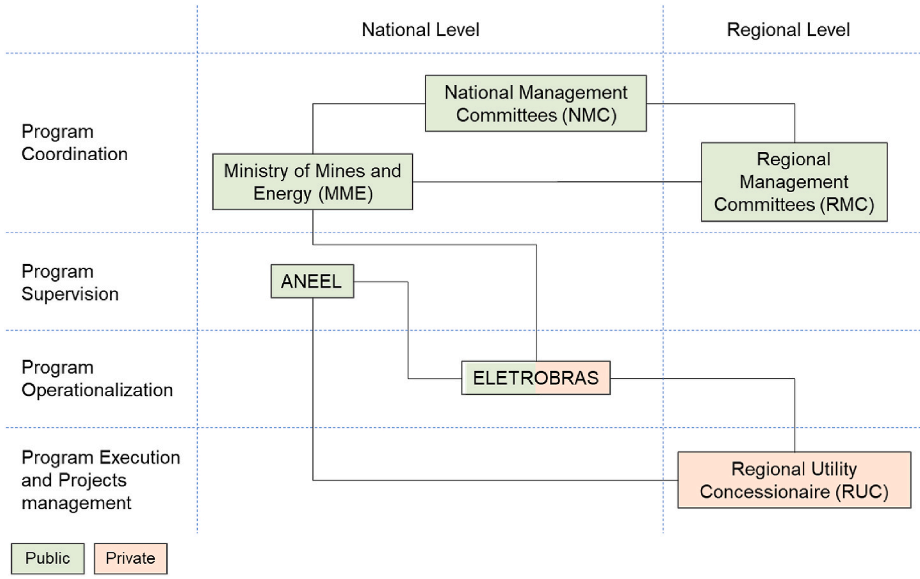

Fig. 1. LPT program's institutional and management structure.

and O&M functions of all projects, being able to externalise some tasks to local companies and community water wells (ANEEL, 2012a; 2012b); the public target extends to ethnic minorities, such as indigenous communities, *quilombolas* (afro-descendant villages), riverside communities, rural settlements and fragile ecosystem communities, such as conservation areas or extractive regions and beneficiaries from other rural development programs (ANEEL, 2012a; 2012b).

To incentivise the assistance to the most remote and low-income communities through decentralised energy systems, an economic subsidy is given to the RUC, aiming to reduce its investment costs. From 80 to 100% of the direct investment costs are provided by the Energetic Development Account (CDE, *Conta de Desenvolvimento Energético*), a sectorial account financed by the consumers of the SIN. CDE also serves to subsidise the fossil fuel-based SISOL through feeding the Fuel Consumption Account (CCC, *Conta de Consumo de Combustíveis)* (ANEEL, 2008a; MME-LPT, 2009; 2013b; 2015a; 2017a). The rest is provided by the RUC, with a variable economical participation from the state, depending on the difficulty in accessing benefited communities. It is worth mentioning that remote systems (LPT, CDE) differ from isolated systems (SISOL, CCC) in Brazilian terminology. While the latter represent only systems isolated from the national grid (SIN), the former are considerably more distant and involve far more complex geographic and socio-cultural characteristics.

Operation and Maintenance (O&M) costs are financed through tariff collection, provided by the end-users. To guarantee its suitability, since 2010 a special discount, the Social Tariff (Tarifa Social), is given to families with incomes less than half the minimum wage, elderly, disabled or low-income groups whose health depends on electrical devices and indigenous or *quilombolas* communities enrolled in the Governmental Single Registry (Cadastro Único). This subsidy consists of a discount that varies gradually according to the level of energy consumption: 65% for 0–30 kWh/month, 40% for 311-100 kWh/month and 10% for 101–220 kWh/month. For indigenous and *quilombolas* communities, electricity is completely subsidised up to 50 kWh/month. Implementation agents (the RUC or third parties) are expected to inform the beneficiaries about the rational use of energy and energy efficiency measures during commissioning. The maximum inspection deadlines and a protocol for tension quality and monthly energy availability is defined and regulated by ANEEL (ANEEL, 2012b; MME-LPT, 2009; 2013b, 2015a, 2017a).

2.2. Venezuela

2.2.1. Rural electrification context

The first initiatives to assist the rural population were carried out by the CADAFE state-owned company in 1959 in response to the massive urban growth and rural exodus (Coing, 2007). In 1985 all the population centres with more than 1000 inhabitants were electrified (López-González et al., 2017a). In 1983, the first National Energy Plan started implementing alternative renewable energies, assisting 5,800 rural inhabitants through micro-hydroelectric energy. In 2000, the Energy and Petroleum Ministry (MENPET) executed the PODER pilot Operative Plan, later replaced by the PER program, in some regions with the purpose of bringing wind and PV solar energy to isolated towns (López-González et al., 2017a). In 2005 electricity coverage was already 96% but one million inhabitants still lacked this service (OLADE - Organización Latinoamericana de Energia, 2017). In the context of the nationalization of private companies, the Foundation for Electrical Development (FUNDELEC), an entity attached to the Electrical Energy Ministry (MPPEE), developed the Sembrando Luz (SL) program. This program is the main focus of the work and is explained in detail in the next section. In 2006, the Energy Revolution Mission was implemented by MENPET with support from the National Electrical Corporation (CORPOELEC); this included five main initiatives: efficient lighting replacement; refrigerator and air conditioning substitution for high-efficiency units; rational and efficient use of energy capacitation programs (MPPEE, 2013a); the implementation of 90 diesel-based energy projects in rural areas (López-González et al., 2019a) which accounts for 1.8% of the 2013 total installed capacity (López-González et al., 2017a) and the Energy tables creation, an organizational system for community empowerment (MPPEE, 2013b). In 2010, the LOSSE law established universal energy access as a right under the responsibility of the State (Asamblea Nacional de Venezuela, 2010) that should be managed by a public model (MPPEE, 2013b). Since then, several plans have been developed at national scale: the 2004–2014 national grid extension Interconnected National System (SIN) increased the network capacity equivalent to 5,900 W (López-González et al., 2017a); the 2007–2013 Renewable Energy Development plan (PDESON) included economic incentives for motivating investment in renewable energies (Jannuzzi et al., 2010); and the 2013–2019 Electric System Development Plan (PDSEN) aimed to bring energy access to 121,000 people through 63 MW of solar and hybrid systems (IRENA, 2015). However, the 400,000 inhabitants without energy access in 2013 (OLADE -

Organización Latinoamericana de Energia, 2017), increased to 500,000 during the following years (IRENA, 2015; López-González et al., 2019a; MPPEE, 2013b).

2.2.2. "Sembrando Luz" program

The SL program was designed with the aim of bringing electricity and drinking water to more than 300,000 inhabitants located in isolated indigenous and border communities (FUNDELEC, 2012; MPPEE, 2013a), aiming to improve life quality, strengthening local organizations' productive activities and endogenous development projects (López-González et al., 2017a). The focus population were permanent, with communities of up to 500 inhabitants organised under a communal council and no electrical power lines within 10 km (FUNDELEC, 2012).

Decentralised renewable-based energy systems were the principal program strategy, encompassing different technologies in relation to the energy source availability, the application purpose and the potential concentration of beneficiaries (López-González et al., 2018a, 2019a). During the first phase, 1,200 Wp and 3,840 Wp PV energy systems (PVS) were applied to improve community services such as schools, health centres, communal houses, canteens, military buildings and natural reserves, among others (FUNDELEC, 2020). Water treatment and desalinization stations and additional pump stations for deeper water sources have also been energised within the program's framework (López-González et al., 2018a). In 2007, a second phase was applied using lower capacity PVS (300 and 600 Wp) to deal with the residential needs of lighting, communication and refrigeration (López-González et al., 2018a). The third period consisted of a twofold strategy: implementation of hybrid microgrids (HMG) in 2009 for community application and the development in 2012 of 1.5 kWp wind-based stand-alone systems (WT) for residential use (López-González et al., 2018a, 2019a). HMG combine wind turbines, PV panels, diesel generators and batteries and are designed to provide up to 2 kWh/day/house, 3.7 kWh/day for health centres and 3.8–7.7 kWh/day for schools (López-González et al., 2018a, 2018b) with a maximum power of 450 VA (López-González et al., 2018a). Energy generation technologies were chosen by considering resource potential, prioritizing wind energy in the northern coastal region and solar energy on the rest of the high isolated territory. All energy systems are subjected to Cuban-Venezuelan joint venture standards and the Venezuela Standard Denomination certification (FUNDELEC, 2012).

The SL program presents a public and state-centered institutional structure (Fig. 2). Due to the Venezuelan institutional structure and the electricity sector's nationalization, all responsibility and direction is centralised in the MPPEE. Thus, the SL decision-making process must have the approval of the MPPEE (López-González et al., 2018a, 2018b).

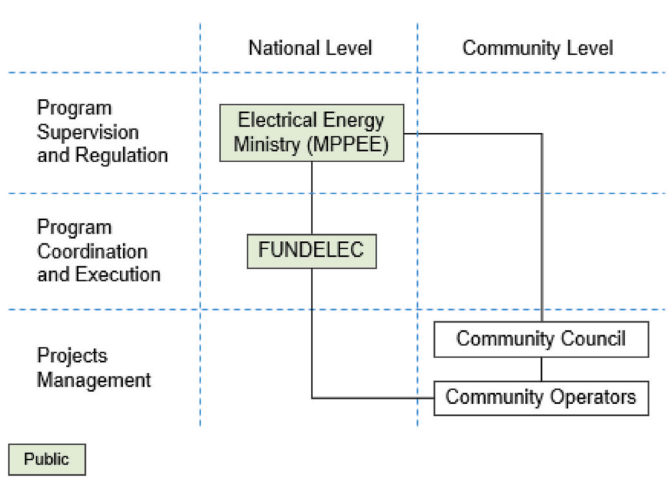

Fig. 2. SL program's institutional and management structure
Source: adapted from (López-González et al., 2018a).

Funding is also managed by the MPPEE through tax collection, mostly from petroleum funds. PV technology has initially been provided by Cuba in return for petroleum, framed within the Cuban-Venezuelan comprehensive cooperation agreement signed in 2000 (IICA, 2014). FUNDELEC is responsible of the integral program design, coordination and execution (FUNDELEC, 2012). Among their responsibilities, a socio-technical diagnostic was developed, aiming to evaluate the social and technical feasibility of projects before the approval decision (FUNDELEC, 2012).

The SL management model is based on the integral participation of the community (López-González et al., 2018a). The O&M of HMG and PVS applied to community services is performed by a Community Operator appointed by the Community Council. Community Councils are composed of representatives of the main beneficiary community. Community Operators are trained by FUNDELEC and financed through community tariff collection. The tariff price, new house connections and techno-economic strategies for economic savings are defined by the Community Council, also in charge of collecting and reporting final users' complaints to the MPPEE (López-González et al., 2018a). Concerning individual PVS and WT, the daily operation and low-skill maintenance is carried out by the users themselves, trained during the implementation phase through communal council meetings (López-González et al., 2018a). Equipment replacement and major maintenance functions are covered by FUNDELEC agents (FUNDELEC, 2012; López-González et al., 2018a). A training program for both beneficiaries and Community Operators has been developed, involving an operational network of regional mobile workshops. Additionally, capacitation activities concerning efficient and rational use of energy are applied by the FUNDELEC team during the energy systems' implementation.

3. Assessment methodology

The assessment methodology consists of a multicriteria comparative ex-post evaluation of the sustainability of the two rural electrification programs (LPT and SL). In order to capture the broad nature of sustainability, 18 ad-hoc indicators are analysed (Table 1), examining issues at the global program level (I1–I7) as well as at the local project level (I8–I18). All the sustainability dimensions have been included. Indicators have been selected considering the availability of comparable information from the two programs and according to previous works related to rural electrification projects and programs evaluations (Domenech et al., 2015, 2019a, 2019b; Gómez-Hernández et al., 2019; Juanpera et al., 2020; Lillo et al., 2015a, 2015b, 2021; López-González et al., 2017b, 2018a, 2018b, 2018c, 2019a, 2019b; Ranaboldo et al., 2015a, 2015b; Triadó-Aymerich et al., 2016). Hence, 18 ad-hoc criteria specific to the application context have been chosen. In addition, the five principles described by Wang et al. (2009) have been observed for the selection of these indicators, the indicators are: 1) systemic, that is, they reflect the essential characteristics of the two programs analysed; 2) consistent with the objective of the study; 3) independent from each other; 4) measurable, either quantitatively or qualitatively; and 5) comparable. Additionally, all the indicators have been validated by scholars and experts from both rural electrification programs, based on their experience in related field-research.

In addition to the peer-to-peer indicators comparison, this work goes one step further and discusses results regarding:

- the program contribution to national rural coverage (D1),
- the beneficiary selection strategy (D2),
- the energy sovereignty development (D3),
- the legal and institutional framework development (D4),
- the management model strategy (D5),
- the economic model (D6),
- the technical strategy (D7) and
- the socioeconomic benefits (D8).

Table 1
Assessment indicators' scale, identification acronym (ID), indicator's name, description, discussion threads (D), indicator type (Qualitative - Ql or Quantitative - Qt), the criteria and references consulted. Qualitative indicators' formulas are detailed in the APPENDIX.

SCALE	Id.	INDICATOR	DESCRIPTION	D	Type	CRITERIA	REFERENCES	
							LPT	**SL**
GLOBAL/ PROGRAM	I1	Technological electrification strategy	Percentage of the DER's configuration (microgrid or individual systems) and the renewable source used (solar, wind)	1, 3, 6	Qt	Institutional &Technical	(ANEEL, 2008b, 2016;Eletrobrás, 2013, 2014, 2015a, 2016b, 2017, 2018a, 2018b)	(MPPEE, 2016)
	I2	Rural Electrification Indicator (REI) variation	Rural electrification target, Percentual increase of rural inhabitants with home access to energy during the program horizon, net program contribution to REI, and REI to complete universalization.	1	Qt	Institutional	(ANEEL, 2008b, 2016; Carvalho, 2019; Eletrobrás, 2013, 2014, 2015a, 2016b, 2017, 2018a, 2018b; IBGE, 2015)	(MPPEE, 2016; WB, 2018, 2020)
	I3	Beneficiaries' profile	Comparison of the initial program priorities and final beneficiaries' profile (geographic, socioeconomic and cultural characteristics)	2	Ql	Institutional & social	(ANEEL, 2008b, 2018a, 2018b, 2019a, 2019b, 2020, 2021a, 2021b; DOU, 2017, 2019a, 2019b, 2020; FUNAI, 2017; IEMA, 2018; MME-LPT, 2013a; MME, 2016; MME-LPT, 2015b, 2017a)	(FUNDELEC, 2012; IPEA et al., 2017)
	I4	Beneficiary Selection Process	Decision makers, main criteria applied and local acceptation condition regarding beneficiary selection	2, 5	Ql	Institutional	(Gama et al., 2013; IEMA, 2018; MME-LPT, 2009, 2013b, 2015a, 2017a; Silva, 2007)	(FUNDELEC, 2012, 2020; López-González et al., 2018a)
	I5	National market development:	Energy market (goods and services) evolution during the program horizon	3	Ql	Institutional & Economic	(ABSOLAR, 2020; SEABRE. Cadeia de, 2018)	(CEPAL, 2004; FUNDELEC, 2012; Grima-Gallardo, 2017; MPPEE, 2013b)
	I6	Policy instruments	Main legal/regulatory and economic/financial instruments applied during the program	4	Ql	Institutional	(Gama et al., 2013; IEMA, 2018; MME-LPT, 2009, 2013b, 2015a, 2017a; Ribeiro, 2015)	(Asamblea Nacional de Venezuela, 2010, IICA, 2014; López-González et al., 2018c[a]; MPPEE, 2013b)
	I7	Funding structure	Percentual origin of the program economic resources and source sustainability	4, 6	Ql & Qt	Institutional & Economic	(MME-LPT, 2009, 2013b, 2015a, 2017a; IEMA, 2018)	(IICA, 2014, López-González et al., 2018a, 2019a; Salas-Bourgoin, 2016)
LOCAL/ PROJECT	I8	Implementation mechanism	Presence of installation and commissioning protocols and evaluation mechanism (process transparency)	5	Ql	Management	(ANEEL, 2008b, 2016; Eletrobrás, 2015b; MME-LPT, 2009, 2013b, 2015a, 2017a)	(MPPEE, 2013b; López-González et al., 2018c, 2018b, 2019a)
	I9	Operation and Maintenance (O&M) model	O&M execution and supervision structure (main responsible entities and procedures)	5	Ql	Management	(ANEEL, 2012b; IEMA, 2018; Jannuzzi, 2009; MME-LPT, 2009, 2013b, 2015a, 2017a)	(FUNDELEC, 2012; López-González et al., 2018a)
	I10	Community capacitation and participation	Local training strategy and community involvement	5	Ql	Management	(Jannuzzi, 2009; MME-LPT, 2007; 2013a, 2015a, 2017a; Ribeiro, 2015)	(FUNDELEC, 2012; López-González et al., 2018a; MPPEE, 2013a, 2013b)
	I11	Levelised cost of energy (LCOE)	Average Net Present Cost of energy for each technological option	6	Qt	Economic	(Moraes et al., 2018; Silva, 2007; Soares et al., 2010)	López-González et al. (2018a)
	I12	Inequality and poverty alleviation	Energy affordability mechanism and minimum family income that guarantees exceeding the energy poverty threshold (percentage of national minimum wage)	6	Ql & Qt	Socio-economic	(ANEEL, 2018c; 2021c; AUDTEC, 2021; MME-LPT, 2009; 2013b, 2015a, 2017a; Poole and Poole JB do, 2001)	(FUNDELEC, 2012, 2020; Inmuebles-Caracas, 2020; López-González et al., 2018a, 2018b)
	I13	Standardization and application purpose	Technological design standardization strategy and percentage of each application's purpose covered by the program (residential, community and commercial)	7	Ql & Qt	Technical	(ANEEL, 2008b, 2012b, 2016; MME-LPT, 2015a, 2017a; 2017b; Valer et al., 2017)	(FUNDELEC, 2012, 2020; López-González et al., 2018b, 2019a)
	I14	Adequacy	Average installed capacity and minimum threshold progress (TIER level)	7	Qt	Technical	(ANEEL, 2008b, 2016; Bhatia and Angelou, 2015; IEMA, 2018)	(Bhatia and Angelou, 2015; FUNDELEC, 2020; MPPEE, 2016)
	I15	Reliability	Minimum autonomy and maximum interruptions (TIER level) and percentage rate of beneficiaries' satisfaction	7	Qt	Technical	(ANEEL, 2008b, 2012b, 2016; Bhatia and Angelou, 2015; Jannuzzi, 2009; MME-LPT, 2017b; Valer et al., 2017)	(Bhatia and Angelou, 2015; FUNDELEC, 2020; López-González et al., 2019a)
	I16	Health	Quantity (%) and capacity (TIER level) of systems installed in health centres and for water pumping and percentage of residential systems solving non-polluting lighting, food safety and clean cooking	8	Qt	Social	(ANEEL, 2008b, 2012b, 2016; Bhatia and Angelou, 2015; Equatorial, 2019)	(Bhatia and Angelou, 2015; FUNDELEC, 2020; López-González et al., 2018b; MPPEE, 2016)
	I17	Education	Quantity (%) and capacity (TIER level) of systems installed in educational centres and percentage of residential systems providing home-education basic needs (light & communication)	8	Qt	Social	(ANEEL, 2008b, 2012b, 2016; Bhatia and Angelou, 2015; Equatorial, 2019)	(Bhatia and Angelou, 2015; FUNDELEC, 2020; López-González et al., 2018b; MPPEE, 2016)
	I18	Incomes	Quantity (%) and capacity (TIER level) of systems installed for productive purposes and comparison of installed capacity and minimum national standards to support productive energy needs	8	Qt	Socio-economic	(ANEEL, 2012a; Bhatia and Angelou, 2015; IICA, 2011; ELETROBRAS, 2016a)	(Bhatia and Angelou, 2015; FUNDELEC, 2020; MPPEE, 2016)

The comparative study highlights the results' interconnections, allowing better identification of the lessons learned in terms of the program's governance strategies (D2, D6, D7), project management mechanisms (D5) and program outcomes (D1, D3, D4, D8). The lessons learned from both universalization programs allow the current strengths and limitations of last-mile electrification initiatives to be highlighted.

The works in the literature commonly group indicators into sustainability criteria, such as institutional, technical, social, economic and management. In that sense, the high presence of institutional indicators (I1–I7) encompasses the global decisions of the main rural electrification promoters, as well as the program's outcomes at a national scale. For their part, social indicators mainly show the local impacts of both rural electrification initiatives. Management indicators are the result of regional decisions and implementation strategies that involve national and local actors. Technical indicators correspond to program strategies with local adaptations and their results at the beneficiary level. Finally, economic indicators are present in most program and project decisions. Therefore, they imply structural decisions and impacts at both national and user levels.

The method used in this research is based on the comparative analysis of case studies, which includes both quantitative and qualitative approaches, as recommended by the literature to successfully address complex problems (Kruyt et al., 2009) (Biresselioglu et al., 2017) (Zaman and Brudermann, 2018). This mixed analysis allows integrating complementary information, giving greater robustness and exhaustiveness to the study. Furthermore, the case study approach allows an in-depth examination of a study topic applied to a specific context, and is especially useful in real-world situations where the causal relationships between phenomenon and context are not evident (Sovacool et al., 2018). In addition, this allows the effective sharing of lessons learned for future similar initiatives (Schnitzer et al., 2014). As is the case, the last-mile of rural electrification requires a higher level of analysis than other electrification studies. Previous experience with last-mile rural electrification programs is essential to improve future universalization initiatives in emerging economies.

The information to evaluate the indicators has been obtained from consultation with several official sources, experts and academic works. Among them, LPT information has been gathered from public consultations with national entities, reports of different involved agents such as ELECTROBRAS, ANEEL, MME and the RUC, and using academic research carried out in Brazil. The national statistical data has also been consulted, as well as legal and regulatory documents. The SL data, in turn, has been obtained from data shared by the MPPE, legal and regulatory documents and reports by national and international institutions. Academic works previously developed by the authors and other scientific articles related to the Venezuelan context have also been considered. Additional details were obtained from participation in the 2020 FUNDELEC conference cycle. All the information has been validated through expert consultations from both programs.

To develop an exhaustive evaluation of LPT and SL, some considerations have been applied to the calculation process and also to harmonise the available information. The SL program has been executed centrally and homogeneously by the national electrification agent, FUNDELEC (López-González et al., 2018a) (FUNDELEC, 2020), whereas in the LPT program each concession area has been electrified considering different RUC criteria. In this sense, the most widespread RUC perspective has been considered for some indicators (I4, I15). Indicators I14 to I18 have been assessed for both programs, applying the multi-TIER framework, an initiative from the ESMAP and SE4ALL entities to capture the multidimensional character of household, commercial and productive energy access (Bhatia and Angelou, 2015). A TIER average has been calculated considering the proportion of each system installed. The calculation details and formulas employed for the quantitative indicators (I1, I2, I7, I11–I18) are described in the Appendixes.

4. Results

This section presents the multicriteria assessment results. Table 2 summarises the results of all assessed indicators. The LPT (Brazil) results are presented on the left and the SL (Venezuela) results on the right. Fig. 3 and Fig. 4 illustrate the principal characteristics of both universalization programs and the results shown in the previous table. Fig. 3 shows the geographical DER distribution, the responsible distribution agencies, the regions that concentrate most of the indigenous population and the remaining regions for universalization. LPT SIGFI connections are presented in Fig. 3.1 and SL direct beneficiaries in Fig. 3.2. It can be seen that, while Brazil is still pursuing universalization in several regions, the SL program has been stopped since 2013 in Venezuela. Fig. 4 presents a Sankey diagram of the different energy system types and capacities installed by each program and their application purpose. Only SIGFI data is presented in Fig. 4.1, as it has proven to be the most widely prioritised technological solution applied by the RUC in Brazil. The SL data is presented in Fig. 4.2.

5. Discussions

The main lessons learned from the last-mile rural electrification experience of Brazil and Venezuela have been analysed using the innovative framework of eight discussion threads. This approach enables the interrelationships between criteria and scales to be assessed and thus pays tribute to the multicriteria and multi-scale nature of sustainability science. These narratives have been generated based on the comparative evaluation of the 18 indicators presented in Table 2 and verified through relevant expert consultations. The contribution of each indicator to the discussion lines construction is shown in Table 1. This novel multicriteria approach generates more in-depth and interdisciplinary analysis regarding sustainable rural electrification practices, as presented in the following eight sub-sections.

5.1. D1: program contribution to national rural electrification coverage (I1, I2)

The common objective of both programs has been the universalization of rural energy access. D1 analyses the starting point, the strategies developed and the final achievement of both programs. The mathematical modelling considered for the calculation of I1 and I2 is detailed in the **APPENDIX**.

DER and, more explicitly, stand-alone PV systems composed the main *program electrification strategy* (I1) to cover remote regions' electricity access in both cases. This common ground highlights the usefulness of this technological strategy in addressing the last-mile of rural electrification.

When the LPT program was launched, electricity coverage in rural areas of Brazil (REI) was 81% (I2). During the entire program horizon, this value increased by 16.8%. This reflects the Brazilian rural electrification efforts. LPT assistance in remote regions was framed within a wider LPT initiative (see section 2.1.2), which consisted of a massive grid extension. The conventional LPT program is responsible for 13.6% of the REI final (Eletrobrás, 2018a). With the completion of rural electricity coverage, concerns have risen about the last-mile of rural electrification. This last-mile has thus been approached with DER and represents 0.2% of the final REI.

The SL program has been developed in a context with 12.0% more rural electrical coverage than LPT (I2) and has focused exclusively on the last-mile of energy connections. Venezuelan REI has increased 0.6% during the program horizon and the direct SL connections are responsible for 0.3% of the final REI. It should be noted that this program has been implemented in tandem with the "Energetic Revolution" national electrification program, where grid and diesel-based electrification have also been applied to rural regions. Additionally, SL addressed rural electrification from a community perspective, prioritizing collective

Table 2
Comparison of the LPT (left) and SL (right) main indicators results. Qualitative indicators' formulas are detailed in the APPENDIX.

IND.	BRAZIL - LPT	VENEZUELA - SL
I1	Decentralised Energy Systems (DER) = 100% of the program's connection in remote regions - 98.7% individual PV systems (SIGFI) - 1.3% PV-based microgrids (MIGDI)	Decentralised Energy Systems (DER) = 100% of the program's connection - 91% individual PV systems (PVS) (31% community applications) - 8% hybrid microgrids (HMG) - 1% individual wind turbines (WT)
I2	*Total REI increase = REI_2018-REI_2003 = 16.8% *Final REI = REI_2018 = 97.8% *Net contribution to REI_2018 (DER) = 0.2% *REI to complete rural universalization (100%) = 2.2%	*Total REI increase = REI_2013-REI_2005 = 0.6% *Final REI = REI_2013 = 93.6% *Net contribution to REI_2013 (DIRECT DER) = 0.3% *Net contribution to REI_2013 (INDIRECT + DIRECT DER) = 4.0% *REI to complete rural universalization (100%) = 6.5%
I3	*Target = (since 2011) indigenous and *quilombolas* communities and northern regions *Result = Uncompleted universalization in north and northeast and for indigenous territories.	*Target = Poorest, isolated and border communities, indigenous villages *Result = 48% of the connections installed in indigenous villages and 52% in isolated border communities. All beneficiaries located in the poorest regions
I4	*Selection process' main decision-makers = RUC (Private) *Main criteria (COELBA): - grid connection cost >6,408 USD (economic) - load demand and supply compatibility (technical) - difficulty of extending grid in preserved areas (environmental) *Subject to beneficiary acceptance	*Selection process main decision-makers = FUNDELEC (Public) *Main criteria (FUNDELEC): - presence of a communal organization (social) - distance to grid >10 km (technical) - fragile ecosystems locations (environmental) *Subjected to Community consensus
I5	* Technology production/energy goods: All small-scale PV production chain currently produced in Brazil * Energy service: national presence of skilled labour for all service types (Installation, O&M, research) and levels (technical, consulting and engineering)	*Technology production/energy goods: Foundation and failure of a national PV and WT manufacturing company. Current status: only assembly functions * Energy services: very low presence of skilled work force
I6	*Legal & Regulatory instruments: 3 laws, 5 decrees, 5 MME Directives, and 4 ANEEL normative resolutions exclusively under LPT framework. Improvement to overcome bureaucratic blocks. No specific legislation for MIGDI *Economic & financial instruments = investment subsidy for SIGFI & MIGDI + economic incentive for MIGDI	*Legal & Regulatory instruments: Law for the Use of Alternative Energy (2013). None for DER, nor under SL program framework *Economic & financial instruments = none but costs fully subsidised by state
I7	* Funding sources – investment: - 80%–100%: CDE account (SIN users) - 0%–10%: RUC - 0%–10%: State government * Funding sources – O&M: CDE account, final users & RUC *Sustainability: SIN users' payments stable but CDE budget decreasing	*Funding source - investment: 100% from the State through: - Petroleum tax collection - Technological exchanges (Cuba-Venezuela cooperation framework) for petroleum * Funding sources – O&M: 100% from the State through Petroleum tax collection *Sustainability: very unstable (subject to market fluctuation prices)
I8	* Installation and commissioning protocol: exists since 2015 for DER. includes technical specifications and control tests * Evaluation mechanism: continuous & ex-post evaluation based on goal fulfilment verification and an accounting-financial audit	*Installation and commissioning protocol = None *Evaluation mechanism = ex-post evaluation based on a single strengths-weaknesses matrix and academic works presented by the authors
I9	*O&M execution: managed by RUC (private). No publicly available procedure *O&M supervision: ANEEL (public) regulates the tariff cost, inspection frequency, energy interruptions and voltage quality	*O&M execution: Participatory Management Model based on final users (PVS & WT) and community (PVS & HMG). Complex tasks made by FUNDELEC (public) *O&M supervision: FUNDELEC agents (public)
I10	*Capacitation strategy: presentation talk and booklet distribution (initial) *Local participation: only spontaneous participations	*Capacitation strategy: initial capacitation during general assemblies and continuous training through mobile regional workshops. *Local participation: existence of trained community operators (HMG & PVS) and negotiation power enhanced through communal council structure
I11	SIGFI 45 = MIGDI 45 (20 houses) = 5.5 USD/kWh (2010)	PVS = 1.605 USD/kWh HMG = 0.273 USD/kWh WT = 3.336 USD/kWh (2018)
I12	*Energy affordability mechanism: energy social tariff for low-income families & extra discount for indigenous and *quilombolas* communities *Energy poverty alleviation (SIGFI45): - Without discount: family income >53% of minimum wage - With discount: family income >23% of minimum wage	*Energy affordability mechanism: completely subsidised (PVS & WT) or tariff decided through community consensus (HMG) * Energy poverty alleviation (HMG): family income >97% of minimum wage.
I13	*Standardization: according to monthly energy availability (kWh/month) and application purpose *Application: 95.1% residential use, 2.0% community applications, 0.0% commercial applications and 3.0% without data.	*Standardization: according to peak power capacity, natural resource availability and application purpose. * Application: 61.2% household application, 38.8 community services, 0% commercial activities.
I14	*Average Installed capacity: TIER2 (household) & TIER3 (community infrastructure) *Minimum threshold progress: from TIER2 (SIGFI13) to TIER3 (SIGFI45)	*Average installed capacity: TIER3 (household) & TIER4 (community infrastructure) * Minimum threshold progress: from TIER2 (300-PVS) to TIER3 (600-PVS)
I15	*Min autonomy = TIER5 *Max interruption = TIER4 but exceeds 92% of the time (COELBA) *Beneficiaries' satisfaction = 76% (COELBA, n = 343)	*Min autonomy = TIER5 *Max interruptions = no limits or audition. * Beneficiaries satisfaction rate = 66.7% for PVS, 58.0% for HMG and 100.0% for WT.
I16	*Community benefits: - systems installed in health centres = < 0.1% (TIER4) - systems installed for water pumping = 0.2% (TIER3). * Residential benefit: - 100% (95.1%) solves non-polluting lighting - 14.2% (13.5%) improves food safety - 0% designed for clean cooking solutions	*Community benefits: - systems installed in health centres = 5.2% (TIER4) - systems installed for water pumping = 8.9% (TIER4). * Residential benefit: - 100% (61.2%) solves non-polluting lighting - 82.1% (50.3%) improves food safety - 0% designed for clean cooking solutions
I17	* Systems installed in education centres = < 2% (TIER3) * 100% allow night education and running media and information devices.	* Systems installed in education centres = 15.7% (TIER4) * 100% allow night education and running media and information devices.
I18	* Systems installed for productive purposes = <0.1% (TIER4)	* Systems installed for productive purposes = 0%

(continued on next page)

Table 2 (*continued*)

IND.	BRAZIL - LPT	VENEZUELA - SL
	* Energy needs for promoted production activities (CCP data) = x4 installed capacity	* Energy needs for promoted production activities = any national data

facilities whose benefits are not reflected in the REI but have demonstrated significant achievements in energy access. In that sense, if indirect beneficiaries are also considered, SL connections would be responsible for 4.0% of the 2013 rural energy access.

In both countries, however, the rural universalization process is not complete. There is still a rural population deficit, of 2.2% in Brazil and 6.5% in Venezuela, to be covered with more rural electrification initiatives. While LPT is still underway and MLA has been launched in Brazil, there is no expectation of continuity for the SL program.

5.2. D2: beneficiaries' selection strategy (I3, I4)

D2 presents the targeted and resulting *beneficiary profile* (I3) and the decisional structure behind *beneficiary selection* (I4). Fig. 3 presents additional information in a geographical context: the assisted and remaining regions, indigenous lands and the distribution companies present throughout the countries.

The LPT beneficiary selection process has been mainly led by RUC from a private-sector perspective and has been heterogeneously implemented throughout Brazil. The main strategy, which has been implemented by the COELBA company (Gama et al., 2013) (Silva, 2007), consisted of techno-economic aspects (I4), diverging from the initially planned socioeconomic criteria (section 2.1.2). LPT program efforts focused on the most energetically excluded regions, mainly in the states of Bahia, Minas Gerais and Pará, but did not complete universalization in the north and northeast regions of the country (ANEEL, 2008b, 2018b, 2019a, 2019b, 2020, 2021a, 2021b). A preferred audience was defined by LPT, prioritizing indigenous populations. However, the location of the installed systems does not coincide with the territories with the highest indigenous concentration (see Fig. 3.1). Less than 5% of the Bahia beneficiary municipalities include indigenous reserves. Considerable evidence exists of unassisted indigenous communities in other regions, such as the Mato Grosso Xingu indigenous reserve (Leite

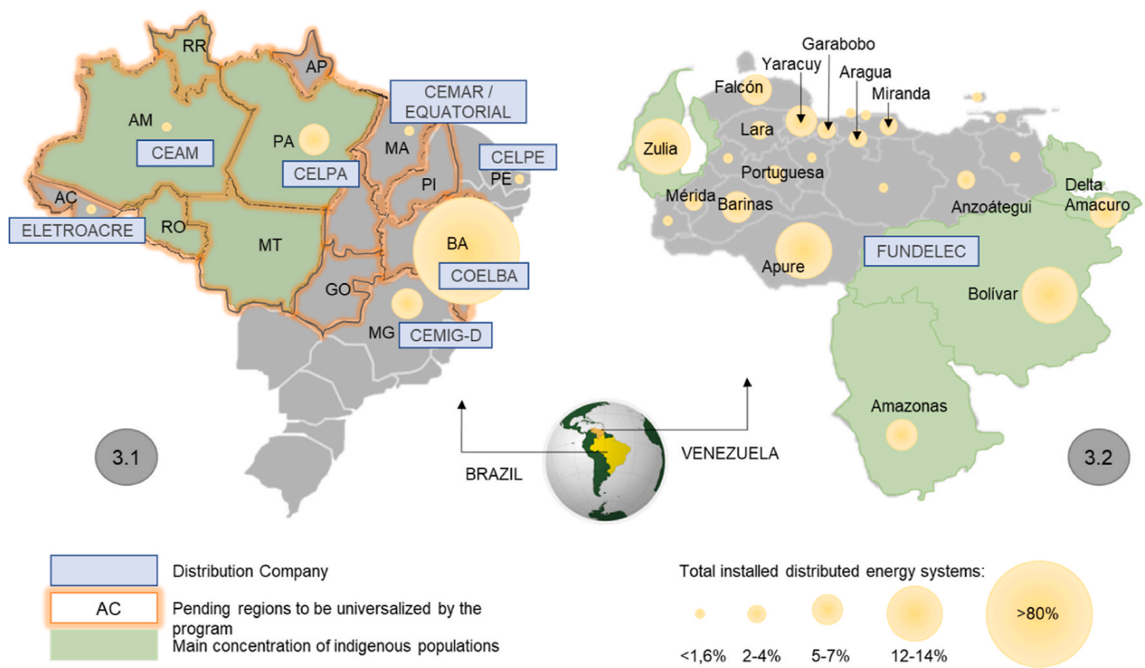

Fig. 3. Assisted and remaining regions, indigenous lands and distribution companies in Brazil (Fig. 3.1) and Venezuela (Fig. 3.2).

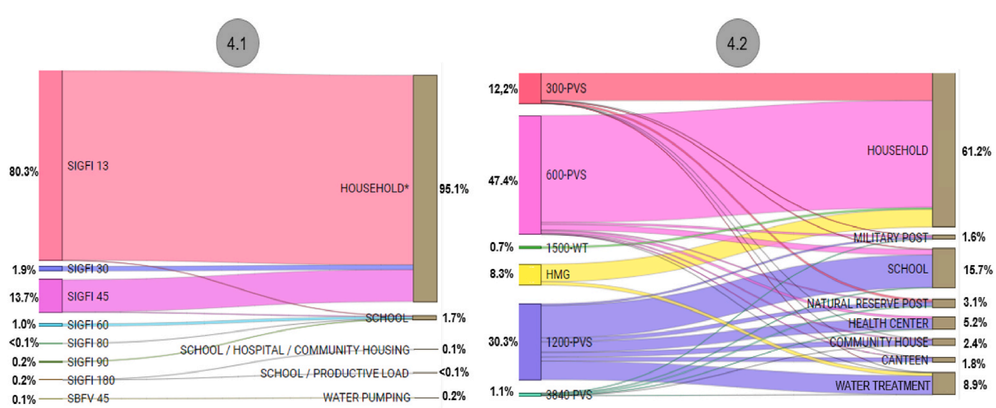

Fig. 4. Sankey diagram of the different energy systems installed for each application purpose during the LPT (Fig. 4.1) and the SL (Fig. 4.2) programs (*CELPA connection taxonomies have been simplified, according to most recent bibliography (ANEEL, 2021c; Equatorial, 2019)).

et al., 2019). The target population was defined but has not been concretised by the LPT program, which has led to subjective interpretations of the program priorities by each RUC. As a result (I3), the most historically excluded regions remain without universal access and most indigenous communities are still neglected.

The Venezuelan program developed a centralised decision-making model with a public perspective. Two specific socio-economic, cultural and geographic profiles were addressed: indigenous populations and isolated border communities with low purchasing power (I3). Social, technical and environmental criteria were applied in the final selection of beneficiaries. The community's cohesion was also prioritised, resulting in equitable assistance between these two commonly neglected communities (I4) (FUNDELEC, 2012; López-González et al., 2018a). The regions with more indigenous communities coincide with the most assisted regions (see Fig. 3.2). SL also reached those municipalities with the lowest HDI (IPEA et al., 2017) and higher rates of extreme poverty than the national average (FUNDELEC, 2012). This coherence between objective and results highlights the success of the strategy both in the design and implementation of the beneficiary selection.

5.3. D3: Energy sovereignty development (I1, I5)

D3 discusses the local and the national energy sovereignty. The former evaluates the adaptation of chosen renewable energy sources to local conditions. The latter studies the energy market evolution during the program horizon. The mathematical modelling considered for the calculation of I1 is detailed in the **APPENDIX**.

The demand for energy solutions in the most isolated Brazilian regions has opened a market opportunity for national manufacturers as well as for research and engineering (I5). Off-grid residential PV energy systems have been the main strategy in remote regions (I1), which has positively influenced the development of the production chain of this particular technology (ABSOLAR, 2020; Jannuzzi et al., 2010; Moraes et al., 2018; Pinho and Galdino, 2014). Free market competition has spurred the creation of energy goods and service businesses based on this technology, especially in the southern and historically more economically developed regions of the country. Inequalities are still present in the territory, leading to unattained regional energy sovereignty in the northern and north-eastern regions of Brazil.

In Venezuela more technology options were considered (I1), adapting local resource availability to the energy system design and reinforcing local energy sovereignty. Within the nationalised market structure, a state-owned company was created in 2012 (I5) to manufacture PV and wind turbines (FUNDELEC, 2012; López-González et al., 2018a; Grima-Gallardo, 2017). Despite the favourable conditions created by the Cuba-Venezuela cooperation agreement (CEPAL, 2004), the lack of political will forced the company into closure in the following years. The national PV and wind industry and the skilled workforce was reduced to mere assembly functions (Grima-Gallardo, 2017). This current lack of national industry is a great barrier to the development of the renewable and decentralised energy market.

5.4. D4: Legal and institutional framework development (I6, I7)

D4 combines the discussion about the main legal, regulatory and financial instruments and the economic incentives applied during both programs. The initial and final state and the legal and institutional framework evolution are also analysed. The mathematical modelling considered for the calculation of I7 is detailed in the **APPENDIX**.

Since the first LPT guidelines for remote regions appeared in 2009 (MME-LPT, 2009) the existing legal and regulatory gap has been filled (IEMA, 2018). The multiagent public-private Brazilian program, together with the continental dimensions of the country, have advanced the development of political instruments (I6). The adaptive application of regulatory rules has overcome some bureaucratic impasses, such as the environmental licensing concern of projects in the northern region (Ribeiro, 2015). The existence of this documentation has also demonstrated the technical viability of DERs. Economic and financial instruments have also been implemented (Ribeiro, 2015) to incentivise the application of these innovative technologies, especially for MIGDI configuration. In that regard, RUC only pay between 0% and 10% of the investment costs (I7). The rest is subsidised by the CDE account, filled by the SIN users' taxes (80–100%) and by state governments (0–10%). SIGFI have been chosen as the best solution for last-mile, but do not meet all the electrification demand, highlighting the need for continuity in financial inducements. MIGDI were more incentivised but had no specific regulation and their implementation fell very short of expectations. Therefore, economic incentives without proper regulation were insufficient to motivate the slightly experienced RUC to overcome the MIGDI investment risk.

The Venezuelan economic model, based on market nationalization, has not stimulated the creation of normative or economical instruments (I6). Due to its centralised execution, the lack of a policy instrument has not been crucial for the favourable application of an innovative technology. The program has also been developed under a fully subsidised public scheme, decoupling the need for financial incentives (I6, I7) from the successful implementation of unprofitable energy systems. However, the lack of regulations can be a long-term impediment to the sustainability of the program, as changes and governmental instability can compromise the replicability, expansion and renewal of the program.

5.5. D5: Management model strategy (I4, I8, I9, I10)

D5 encompasses the evaluation of different management stages: the implementation mechanism and the O&M model. Transparency is discussed in terms of the publication of installation and commissioning protocols and evaluation mechanisms. The main entities responsible for execution, supervision and procedures are also considered. Finally, the community capacitation and participation and some local acceptation conditions are also compared.

Despite the large number of agents involved, the Brazilian management mechanism guaranteed harmonised implementation throughout its territory. Since 2015, quality and safety standards have been compiled to regulate the start-up of the new projects (I8). The correct fulfilment of these standards is verified by the regulation and coordination authorities ANEEL and ELETROBRAS, respectively, as a requisite for funding release. However, the O&M protocols are not clearly defined (I9) and their execution is carried out confidentially by the RUC. The only control mechanism corresponds to the validation of a series of parameters, measured and sent semi-annually by the RUC. The supervisory agent has a passive role and it is the responsibility of the RUC to send the requested information (ANEEL, 2008b; 2012b, 2016). During the systems' implementation, the RUCs were responsible for conducting community training that included the distribution of inclusive booklets. The effectiveness of this initial intervention, as the main LPT training strategy, has been discussed by some scholars (Ribeiro, 2015). Local participation has occurred only during the system's implementation, due to the lack of skilled-labour in the remote regions. In that sense, the absence of an adequate and continuous community training mechanism, combined with a lack of attention on the part of the RUC, can compromise the long-term durability of the systems (I10).

Conversely, the Venezuelan management model did not include official or publicly available protocols or any recorded state-promoted evaluation (I8). No publication has been found related to the O&M procedures carried out by FUNDELEC, or the monitoring of the operating status of installed systems (I9). This lack of information sharing can compromise the management model's transparency. For its part, SL obtained a similar level of coordination without any commissioning protocol, thanks to its centralised implementation. In addition, community empowerment has been one of the program's pursued outcomes. The O&M strategy stands out (I10), combining the work force of final users, community operators and the FUNDELEC agents within a participatory management model. Ongoing training of community operators ensured the ability to perform simple and medium O&M tasks. Besides, the need for a community council structure as a prerequisite for selection (I4) guarantees community bargaining power as a tool to avoid misunderstandings by the distribution agent when performing more complex O&M tasks.

5.6. D6: Economic model (I1, I7, I11, I12)

D6 analyses the economic model considering top-down and bottom-up approaches. First the LCOE and the sustainability of financing of each of the technological electrification options are discussed. Then, the final user costs are studied in terms of the existence of inequality and poverty alleviation mechanisms. The combination of both perspectives allows the weakness and strengths of each economic model to be understood. The mathematical modelling considered for the calculation of I1, I7, I11 and I12 is detailed in the **APPENDIX**.

The LPT program is principally financed by the CDE, an account fed by the SIN users through tax collection. This system represents a stable financing source (I7). However, the CDE also subsidises the fuel-based SISOL energy systems (see section 2.1.1 and 2.1.2); while the LPT funds are decreasing, the SISOL funding increased from 2013 to 2018 (IEMA, 2018). This highlights the institutional prioritization of fossil fuel-based generation systems for isolated communities (SISOL) versus renewable energy systems for remote regions. MIGDI and SIGFI have a similar LCOE for a 20-house village (Soares et al., 2010) (I11). Microgrids are slightly cheaper in more densely populated communities, but this technical solution has been largely disregarded (I1).

The SL funding structure (I7), in turn, depends exclusively on petroleum tax collection, which is the prime source of national public revenue in Venezuela (Salas-Bourgoin, 2016). This financial structure is very risky due to its instability and dependence on external market fluctuations (López-González et al., 2019a). However, the public and centralised structure resulted less expensive by avoiding distributor costs and implementing different innovative and less profitable energy solutions more effectively than the Brazilian scheme (I11). Regarding the different technologies implemented, HMG are clearly an economic alternative and WT the most expensive. However, the large proportion of installed PVS (I1) shows that technological choice has not focused solely on cost optimization, but has also considered local conditions and application purposes.

Finally, both programs applied energy affordability mechanisms (I12) to guarantee energy access at a reasonable end-user cost. The Venezuelan strategy consisted of a fully-subsided scheme for PVS and WT beneficiaries and a partially financed HMG rate based on community consensus. The Brazilian program, in turn, applied a partially subsidised social energy tariff with scaled discounts according to consumption and socioeconomic profile. A higher discount was given for indigenous and *quilombolas* communities to avoid inequalities in energy access.

5.7. D7: Technical strategy (I13, I14, I15)

D7 compares both programs' technological standardization and application purposes (residential, community and commercial). In addition, the average installed capacity, the minimum threshold progress, minimum autonomy and maximum interruptions are discussed according to the Multi-TIER framework. The beneficiaries' satisfaction rates are also presented. The mathematical modelling considered for the calculation of I13, I14 and I15 is detailed in the **APPENDIX**.

The two programs have implemented a *Technological standardization* according to the *application purpose* (I13). The LPT model stipulates the minimum energy availability to be guaranteed in each concession area and fulfilment of this requirement is audited by the supervisory agent. This standardization procedure has led to a good mechanism for an equitable dimensioning throughout the vast Brazilian territory, considering the diversity of solar energy resource potential, load profiles and the large number of actors involved. The stipulated energy outcomes were designed for residential energy demands, which justifies 95.1% of remote applications being focused on electrifying households.

The Venezuelan program applied several standard models designed for specific locations and application purposes (I13), optimizing the use of natural resources and the fulfilment of social compliance. These technological models, framed within the Venezuelan Standard Denomination, have incorporated different energy resources, such as wind and solar, and have been similarly implemented for both residential and community applications. This approach has led to a good implementation strategy for a territory with similar energy-environmental characteristics and has favoured community applications.

In both countries, the 48-h energy system autonomy of LPT and SL allows provision of reliable energy access (I15) based on the multi-TIER framework (TIER5). However, more effort is needed with regard to energy interruptions. In Brazil, data presented by COELBA regarding quality evaluation (ANEEL, 2008b, 2016), points out that the maximum monthly interruption limit has been exceeded 92% of the time. In Venezuela, no limitation or audition mechanism has been established regarding interruption frequency. Beneficiary satisfaction rates show positive system performance in both countries but also reveal a dissatisfied section of the population that should be addressed with further research.

The household energy availability (I14) has been improved over both program horizons, passing from TIER2 to TIER3. Due to the limitation of SIGFI13 and SIGFI30 in guaranteeing food refrigeration (Gama et al., 2013), since 2015 only SIGFI45 and above have been installed under the LPT program. However, the latter represents less than 10% of all installed systems (Fig. 4.1). In Venezuela, a similar progression occurred with 300-PVS and 600-PVS. The latter represents, however, the most installed capacity (Fig. 4.2). Finally, SL achieved a higher performance than LPT in both residential and community applications, with TIER3 and 4 respectively for Venezuela and TIER2 and 3 for Brazil.

5.8. D8: socioeconomic benefits (I16, I17, I18)

D8 evaluates the advantages and limitations, in terms of social contributions, offered by each program. Health, education and income generation activities are discussed considering the quantity and capacity of systems installed for each purpose, considering the Multi-TIER perspective. Results are graphically presented in Fig. 4: the Brazilian program has prioritised household benefit over community infrastructure improvement (Fig. 4.1) while the Venezuelan strategy has focused on a broader range of socioeconomic welfare (Fig. 4.2). The mathematical modelling considered for the calculation of I16, I17 and I18 is detailed in the **APPENDIX**.

Both programs improved the residential life quality by enabling home-schooling through lighting and access to information and communication technologies (I17). The possibility of refrigerated loads enables food safety (I16), which is guaranteed for only 14.2% of the residences under the LPT program, in comparison with 82.1% of the residences served with SL. This social benefit is only possible with higher capacity systems. Both programs present a residential transition from TIER2 to TIER3 and, observing the average TIER in both cases, addressing food safety stands out among SL priorities while only being a late achievement for LPT. Despite being a crucial concern of the South, clean cooking solutions (I16) remain a challenge for both countries.

The SL program has also outperformed LPT for community applications (I16, I17). Schools, community water wells and health centres have been electrified with TIER 4, which is considered a coherent energy supply from the Multi-TIER perspective, accounting respectively for 15.7%, 8.9% and 5.2% of all SL connections. In addition, the SL program has gone a step further, improving nutrition at schools through the electrification of school canteens (1.8%). On the other hand, less than 2.1% of the LPT connections are framed within this category. Each RUC applied its criteria in the dimensioning of community energy needs, resulting in an average TIER3 level for schools and water systems and TIER4 for health centres.

Neither of them has managed to develop energy solutions to strengthen productive activities, despite this being one of the main objectives of both universalization programs (I18). An attempt has been made during the LPT program, with the creation of the Community Production Centres (CCP). However, the technical specification considers applications with an energy demand of 720 kWh, which is four times higher than the maximum installed capacity within the whole LPT program (ELETROBRAS, 2016a). In Venezuela, installed systems have not been applied to productive activities, despite the fact that the 3840-PVS (TIER5) could perform these functions in small applications.

5.9. Lessons learned

The comparative evaluation of last-mile electrification strategies applied in LPT and SL programs resulted in 8 main lessons learned:

- D1: the last fraction of the Rural Electrification Indicator (REI) corresponds to the last-mile of rural electrification. The LPT and SL experiences regarding this challenge have confirmed the suitability of renewable-based Distributed Energy Resources (DER).
- D2: a decision-making process led by private companies has prioritised the economic and financial profitability aspects. In contrast, a decision-making process carried out by public organizations turned out to be a good mechanism to ensure energy access and avoid energy inequalities for the most isolated and commonly neglected populations.
- D3: a program that involves private companies and subcontracting activities in a competitive free market context has motivated the development of a national renewable energy market. A public program developed by a state-owned company has prioritised local energy sovereignty.
- D4: a distributed and multi-agent program execution has incentivised the dynamic creation of policy instruments. In a state-centered program execution, on the contrary, policy instruments have not been promoted, conditioning the program's long-term sustainability and hindering future initiatives.
- D5: a well-defined installation and commissioning protocol has proven useful in ensuring the quality of project implementation under distributed program execution. Furthermore, a participatory management model accompanied by institutional support resulted in a successful strategy to strengthen local empowerment and energy capacities in remote regions.
- D6: a stable and sustainable financing source throughout the project horizon is essential to guarantee the continuity of electrification activities, especially for low-income beneficiaries where maintenance tasks need full or partial subsidies. The public structure has offered advantages over the public-private partnership, such as a more effective implementation of different energy solutions.
- D7: the standardization of technological models, with a defined source of energy, power and purpose in a particular socio-geographic context, resulted in an efficient mechanism for achieving goals. Output standardization ensured an equitable design in a complex and extended application territory.
- D8: LPT has focused on a rapid household energy coverage, while SL has prioritised collective charges and has improved education and health centres' energy access. Energy sufficiency is a critical element for transformative socio-economic contributions. From the multi-TIER perspective, TIER 3 turned out to be the minimum access level to ensure food security. To promote productive activities and clean cooking solutions effectively, there is a need for installed capacities and initiatives focused specifically on these purposes.

6. Conclusion and policy implications

Achieving universal access to energy remains a challenge for the Global South. In particular, territories shaped by geo-socio-environmental complexity, where the only viable technical option requires complex energy solutions, are the remaining regions to be electrified. Together, these ingredients form the recipe of last-mile rural electrification. The experiences of already implemented major rural electrification programs can provide knowledge for avoiding or anticipating errors, can replicate successful strategies and be drivers for sustainable development. However, the evaluation of these initiatives is still poorly documented and discussed in the literature.

The objective of this work is to address this gap, offering an ex-post comparative evaluation of the main last-mile rural electrification programs applied in South America: the Brazilian "Luz Para Todos" and the Venezuelan "Sembrando Luz". Both programs have similarities that ensure their comparability and, at the same time, have context-dependent characteristics, which makes these two case studies appropriate candidates to build an analysis of last-mile strategies and their long-term outcomes. To do so, a novel multi-scale and integrative perspective has been implemented, enabling the extraction of eight discussion threads. Each topic encompasses the main experiences and lessons learned from both universalization programs, obtained through the evaluation of 18 ad-hoc indicators. These indicators meet the multi-criteria decision analysis principles (systemic, consistency, independency, measurability, comparability (Guedes, 2020)), and have been selected based on similar works from the literature and under the consultancy to scholars and experts from both universalization programs. It can be noted that the narratives generated by the discussion threads covers all the sustainability dimensions and includes the local-project and global-program scales. In addition, this novel perspective goes through the different program stages, extracting conclusions and meaningful insights regarding the design and implementation strategies and the outcomes obtained by each program.

Considering the discussion threads and the lessons learned from the "Luz para Todos" (LPT) and "Sembrando Luz" (SL) universalization programs, renewable-based distributed energy resources (DER) an adequate option for remote regions from a sustainability perspective. Although off-grid solutions are already a mature technology, there is still many barriers to overcome. Its application in last-mile rural electrification programs should continue to be tested, validated and improved through ex-ante, intermediate and ex-post assessments, promoted by rural electrification stakeholders.

The combination of technological standardization, the existence of legal and institutional instruments, financial incentives and the presence of the DER national market are necessary but insufficient to motivate the use of this technology to cover the last-mile of rural electrification. Due to the causal relationship of these elements with the development and sustainability of energy initiatives, some recommendations can be drawn to improve the energy governance of universalizing programs. First, the technologies used must be supported with adequate legislation for implementation and operability. Specific legislation has to be developed by public institutions with the support and consultancy of the different stakeholders at the national level, through public and participatory processes (public hearings, for example). Second, the use of last-mile available energy resources should be promoted as far as possible. That is, to prioritise locally available renewable sources and technologies developed at the national level. The national market must be promoted by rural electrification actors, emphasizing the technology transfer in future international cooperation projects. Third, the last-mile of rural electrification is, by definition, the most complex and costly phase to electrify. Financial incentives are essential both to cover losses and offset investment risk by distribution companies, and to counterbalance maintenance costs for beneficiaries, who often live under poverty conditions. More specifically, the comparative study has revealed that the institutional tools applied to public companies have been more effective than economic incentives to private companies for implementing innovative technologies with a social purpose. This unravels the role of public organizations in energy universalization programs.

In addition, a stable financing source is essential both to guarantee programs' access to all last-mile users and to ensure the long-term maintenance and durability of the systems. Therefore, it is recommended that future last-mile electrification programs incorporate maintenance plans, which includes equipment renewal and capacity expansion, promoted and accompanied by public and private stakeholders with the economic support to guarantee the long-term sustainability. In addition, models that support community organization, incorporate local training programs and based on participatory management are highly recommended and should continue to be investigated.

Finally, the socioeconomic outcomes observed highlight the need to give more importance to food security and clean cooking solutions from the programs' plan. The promotion of income generating activities needs more institutional intervention and a site-specific participatory design. Community education and health improvement need to be promoted through more community infrastructure, so that energy access can create real opportunities. Long-term field research is especially needed to incorporate into the outcome analysis, the real impacts of last-mile electrification programs from the benefited population perspective.

These lessons learned from Brazil and Venezuela are general insights applicable to other last-mile contexts in Latin America, Asia and Africa, and are intended to strengthen universal and durable access to clean energy around the world. It is thus vital to continue with scientific research efforts towards developing drivers to create synergies and overcome current barriers to universal energy access.

CRediT authorship contribution statement

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

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.

Acknowledgments

This research was funded by the Spanish Ministry of Science, Innovation and Universities (research project RTI2018-097962-B-I00), and cofounded by the Centre of Cooperation for Development (CCD) of the Universitat Politècnica de Catalunya (UPC-BarcelonaTech) (predoctoral scholarship 2019).

We thank the two anonymous reviewers for their useful comments and constructive suggestions.

APPENDIX

INDICATOR	FORMULA
I1. Percentage of the DER's configuration and the renewable source used	$\frac{DER_i}{\sum_{\forall i} DER_i}$ where DER_i is the number of systems installed of technology i
I2. Rural Electrification Indicator (REI) variation	*** Total REI increase during the program horizon:** $REI_N - REI_0$ where: $REI_n = \frac{Population\ with\ energy\ access\ in\ year\ n}{Total\ rural\ population\ in\ year\ n}$ and N the final program year. *** Net program contribution to REI:** $\frac{Total\ program\ beneficiaries\ in\ year\ N}{Total\ rural\ population\ in\ year\ N}$ *** REI to complete universalization:** $1 - REI_N$
I7. Funding source	The funding sources were presented in previous works from Brazil (MME-LPT, 2009; 2013b, 2015a, 2017a; IEMA, 2018) and from Venezuela (IICA, 2014; López-González et al., 2018a, 2019a; Salas-Bourgoin, 2016).
I11. Levelised cost of energy (LCOE)	The LCOE was estimated in previous works from Brazil (Soares et al., 2010) and Venezuela (López-González et al., 2018a), using HOMER.
I12. Inequality and poverty alleviation	This indicator calculates the ratio between the average expenses on energy and 5% of the national minimum wage, as an indicator of the minimum family salary to overcome energy poverty line. $\frac{1}{N}\sum_{n=0}^{N}\frac{Energy\_Tarif_n}{\frac{5}{100}*Minimum\_wage_n}$ In Brazil, two types of tariff (with and without the energy social tariff discount (ANEEL, 2018c)) have been considered for the SIGFI45 technology (MME-LPT, 2017a). The national minimum wage and the energy tariffs consider the whole program horizon (n = 2004:2018). Data has been gathered from (AUDTEC, 2021) and (ANEEL 2021c; Poole and Poole JB do, 2001) respectively. In Venezuela, only HMG have been assessed as PVS and WT are fully subsidised. The average HMG tariff has been obtained from (López-González et al., 2018a, 2018b) and the minimum wage has been gathered from (Inmuebles-Caracas, 2020), based on the program horizon (n = 2005:2013).
I13. Energy services application type	$\frac{Systems_j}{\sum_j Systems_j}$ where $Systems_j$ is the number of systems installed for the application j (household application; community service; commercial activity)
I14–I18. The Multi-TIER framework	The multi-TIER framework (Bhatia and Angelou, 2015) was developed in order to quantify the access to energy from a multi-criteria perspective.

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INDICATOR	FORMULA
	Different types of multi-TIER applications have been defined: o $k = 0$: access to household electricity services o $k = 1$: access to household electricity supply o $k = 2$: access to productive activities o $k = 3$: Access to health centres o $k = 4$: Access to water pumping systems o $k = 5$: Access to educational centres For each application k, the access level $TIER_k$ is calculated as: $TIER_k = \sum_i \frac{DER_i}{\sum_i DER_i} * TIER_{i,k}$ where $TIER_{i,k}$ corresponds to the service level provided by technology i for the application k, calculated as: $TIER_{i,k} = MIN_{\forall j} TIER_{i,j,k}$ where $TIER_{i,j,k}$ is the service level provided from the perspective of multi-attribute j; and the minimum multi-attribute is considered. The attributes are specified in the rows below.
I14. Adequacy	* **Average installed capacity in households** ($k = 1$): $j = 1$ (peak capacity) * **Average installed capacity in community infrastructure** ($k = 3:6$): $j = 1$ (peak capacity)
I15. Reliability	* **Minimum autonomy in households** ($k = 1$): $j = 2$ (availability) * **Maximum interruption periods in households** ($k = 1$): $j = 3$ (reliability)
I16. Health	* **Average TIER installed for each community infrastructure** ($k = 3:5$): $j = 1$ (peak capacity); $j = 2$ (availability); $j = 3$ (reliability); $j = 4$ (quality); $j = 5$ (affordability); $j = 6$ (legality); $j = 7$ (convenience); $j = 8$ (health), $j = 9$ (safety) * **Average TIER installed for household services** ($k = 0$).
I17. Education	* **Average TIER installed for each community infrastructure** ($k = 3:5$): $jj = 1$ (peak capacity); $j = 2$ (availability); $j = 3$ (reliability); $j = 4$ (quality); $j = 5$ (affordability); $j = 6$ (legality); $j = 7$ (convenience); $j = 8$ (health), $j = 9$ (safety) * **Average TIER installed for household services** ($k = 0$).
I18. Incomes	* **Average TIER installed for productive activities** ($k = 2$): $j = 1$ (peak capacity); $j = 2$ (availability); $j = 3$ (reliability); $j = 4$ (quality); $j = 5$ (affordability); $j = 6$ (legality); $j = 7$ (convenience); $j = 8$ (health), $j = 9$ (safety)
I16–I18. Percentage of systems installed for each purpose	$\frac{DER_{i,k}}{\sum_i DER_{i,k}}$ where $DER_{i,k}$ is the number of systems of the technology i, installed for the purpose k (with k from 2 to 5)
I18. Energy needs for promoted production activities	$\frac{Capacity_{CCP}}{Capacity_{installed}}$ where $Capacity_{CCP}$ corresponds to the capacity recommended for productive activities in the CCP reports (Eletrobrás, 2016a) and $Capacity_{installed}$ is the average installed energy capacity in Brazil for productive activities. No public data was available for Venezuela.

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