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Driving Innovation for Sustainable Rural Electrification: Integrating Technology, Governance, and Business Models

Abstract:

Purpose: This study analyzes existing management model configurations of rural electrification projects to help organizations successfully carry out these projects, ensuring both innovation and sustainability.

Methodology/Design: The research methodology employs a systematic literature review, providing a comprehensive analysis of 37 publications, including 95 case studies selected from an initial pool of 175 publications. Bibliographic and content analyses were conducted on the management model configurations found in each case study.

Findings: The analysis identifies and highlights key issues in managing rural electrification projects, expanding the knowledge base by uncovering innovative configurations and integrating them into a comprehensive conceptual framework. Key findings include the predominance of off-grid solutions, reliance on non-conventional resources, the prevalence of fee-as-a-service models allowing users to manage costs periodically, and the necessity of addressing governance, technology, and business model dimensions.

Originality/Value: This study validates and extends a framework for the innovative and sustainable management of rural electrification projects based on an extensive review of case studies. It contributes to the field by uncovering novel management model configurations and integrating them into a conceptual framework that offers valuable insights for organizations involved in rural electrification.

Keywords: Innovation, Sustainability, Management, Rural Electrification, Energy access

Type: Original Article, Research Paper

1. INTRODUCTION

Access to energy is a fundamental prerequisite for achieving sustainable development on a global scale (World Bank, 2018). Since the formulation of the Sustainable Development Goals (SDGs) within the 2030 Agenda, numerous initiatives have emerged to fulfill the primary objective of SDG 7: ensuring universal access to energy by 2030. Nevertheless, despite concerted efforts, achieving this goal remains unlikely, with an estimated 660 million people projected to lack access to energy by 2030 (World Bank, 2021).

The challenge of achieving universal access is increasingly complex, as most unelectrified populations reside in remote areas with challenging orography, which complicates energy supply (Gómez & Silveira, 2015). Approximately 85% of the world's population without energy access lives in rural areas (Bueno-Lopez et al., 2019). This lack of energy access poses severe health issues, such as the inability to preserve food, constant exposure to toxic fumes while cooking, and educational barriers caused by the absence of lighting (ESMAP, 2019). Additionally, providing energy access in

these often requires investments that are difficult to recoup, as residents cannot the full costs, and maintaining expenses are heightened due to the need for technicians to travel to remote locations (Mainali & Dhital, 2015).

Although grid extension remains the primary method of providing energy access, it is generally unsuitable for isolated, hard-to-reach rural areas (Garces et al., 2021). Smaller scale solutions are therefore imperative to meet the needs of inhabitants without incurring unaffordable investment and maintenance costs (Terrapon-Pfaff et al., 2014). Off-grid systems are the most common solution in such cases, as they avoid reliance on traditional energy sources or fossil fuels, which are less sustainable socially, environmentally and economically (Katre et al., 2019).

Importantly, SDG 7 focuses not only on universal access but also on ensuring that such access is affordable, efficient, clean, and sustainable (United Nations, 2015). Simply adopting small-scale technology does not guarantee project sustainability or affordability, as selecting suitable technology for rural contexts is insufficient on its own (Gómez-Hernández et al., 2019). Instead, implementing effective management models is essential to ensure the sustainability of rural electrification projects (Bhattacharyya, 2013). Practical decision-making tools are needed to simplify day-to-day management and align project practices with long-term objectives (Rekonen & Björklund, 2016).

Multiple management models exist for rural electrification projects, yet no universal framework guides the selection or the evaluation of these models for specific project types (Bazilian et al., 2012). Furthermore, existing literature lacks consensus on terminology, and many theoretical models fail to address the realities of such projects, often inappropriately applying practices from developed countries to developing one without adequately considering local needs and contextual characteristics (Del-Río-Carazo, Iglesias-Pradas, et al., 2022). Establishing adequate management models is key for project sustainability (Palit, 2013) and helps promote technology adoption, reduce inequalities, and strengthen individual empowerment within rural communities (Lillo, Ferrer-Martí, Fernández-Baldor, et al., 2015).

Previous research has synthesized potential configurations of management models for rural electrification projects (Del-Río-Carazo, Acquila-Natale, et al., 2022) based on a limited number of case studies. This research identified three critical dimensions: governance, technology, and business. Building upon these dimensions, the present study validates and expands existing management model configurations for rural electrification projects through a comprehensive systematic literature review encompassing a wide array of case studies. This approach is similar Díaz-Puente et al.'s (Díaz-Puente et al., 2023) study on innovation project implementation in developed countries but focuses specifically on innovation and sustainable management in electrification projects within developing countries.

This study begins with an overview of the current state of rural electrification management models. It then presents findings from a systematic literature of 95 rural electrification case studies. The results reveal novel management model configurations, which are analyzed and integrated into the conceptual framework, offering valuable insights for future project developers.

2. BACKGROUND

When considering an energy access project, the prevailing approach often focuses on the technology intended to provide access to the project's beneficiaries (Ranaboldo et al., 2015). Traditional approaches to rural electrification have historically overlooked essential aspects such as maintenance and affordability (Schillebeeckx et al., 2012). However, management practices in these interventions directly impact sustainability of projects (León et al., 2020; Lillo, Ferrer-Martí, Fernández-Baldor, et al., 2015; Zangara & Filice, 2024).

Developing a management model for such projects requires consideration of numerous variables.

Currently, no universal framework guides decision-making at this level, and existing frameworks are either unidimensional or use inconsistent terminology for each aspect, making them unsuitable as references. For example Chaurey *et al.* (2012) outline considerations related to affordability, financing, ownership, maintenance, and institutional relations, while Schillebeeckx *et al.* (Schillebeeckx *et al.*, 2012) propose a framework that emphasizes end-users, placing them at the center of the issue and exploring their needs, the roles of communities, and resource constraints.

To address these limitations, Del-Río-Carazo *et al.* (2022) propose a configurable model based on an analysis of three off-grid rural electrification projects that use photovoltaic solar energy as their generation source. These case studies represent private initiatives, each characterized by significant differences in governance and business models. Their model identifies the key factors to consider during project management design, categorizing each factor into three dimensions: governance, technology, and the business model (Chaurey *et al.*, 2012; Eras-Almeida *et al.*, 2019).

The framework proposed by Del-Río-Carazo *et al.* (2022) offers a comprehensive, multidimensional approach that integrates governance, technology, and business model factors. This integration distinguishes it from other models in the literature, which often focus on single aspects. For example, Chaurey *et al.* (Chaurey *et al.*, 2012) primarily address financial considerations, while Eras-Almeida *et al.* (Eras-Almeida *et al.*, 2019) focus on governance structures. Unlike these more narrowly scoped frameworks, the model by Del-Río-Carazo *et al.* (Del-Río-Carazo, Acquila-Natale, *et al.*, 2022) accommodates multidimensional management models, making it particularly effective in complex contexts. These include rural electrification projects in developing countries, where variations in governance structures, socio-economic conditions and available financial resources demand a flexible, integrative approach.

2.1 Governance model

A project's governance encompasses three essential facets: project ownership, service operation, and interrelationships among stakeholders. When considering project ownership, careful thought is required to determine who will drive the project forward, as each option has its own set of advantages and drawbacks. State-owned projects often benefit from assured financing (Greeley, 1986) but may encounter challenges in maintaining operational efficiency (Gölz, 2005), especially compared to projects owned by municipalities or local entities. In contrast, private initiatives have the financial resources needed to ensure equipment effectiveness but rely heavily on community engagement for success (Horiuchi, 2018). In some cases, private entities may promote projects and donate equipment to a community group, which then assumes ownership and operates as a cooperative (Yadoo & Cruickshank, 2010). In such cases, cooperative members are usually responsible for operations, although other actors may share these responsibilities (Madriz-Vargas *et al.*, 2016).

Partnerships play a key role in these projects. Following the definition of the SDGs, collaboration between public and private entities (Public Private Partnerships, PPP) became imperative to achieving these goals (Leal Filho, 2018). Additionally, institutions such as universities, non-profit organizations, and banks can contribute to SDGs and be integrated into the planning and execution of these interventions through collaborative 5P models (Sovacool, 2013).

2.2 Technological model

At the technological level, rural electrification projects are meticulously designed, considering factors such as location, population density, and resource availability (IEA, 2020). On-grid systems are employed when the target community is near an already electrified area, as costs are relatively manageable for electricity providers and governments (Nagarjun, 2015). However, when extending the grid is not feasible, off-grid solutions become necessary, including micro-grids for densely populated areas (Gullberg *et al.*, 2005) or isolated systems for sparsely distributed populations

(Mandelli et al., 2016). The selection of energy sources depends on the chosen technology and the area's resource availability. Conventional technologies rely on fossil fuels (Bernardo & Kilayko, 1990), while non-conventional technologies rely exclusively on renewable energy sources (Horiuchi, 2018). Hybrid technologies combine both conventional and renewable energy sources (Chakrabarti & Chakrabarti, 2002).

2.3 Business model

Affordability of energy access is essential for achieving sustainable development (Franco et al., 2020). Consequently, new payment and service models have emerged to enable communities to access energy at costs affordable for their household economies (Morris et al., 2007). Some payment models exclude equipment maintenance costs, with the equipment either financed or sold to communities at specific points in time. However, the customer-seller relationship typically does not extend beyond these acquisition agreements (Ottinger & Bowie, 2016). In general, projects where users purchase a service from the project promoter—who is responsible for maintaining or replacing the equipment in exchange for a monthly fee—tend to be more successful (Painuly & Wohlgenuth, 2008). This fee can be paid after the energy has been consumed, similar to models in developed countries, or in by purchasing periods of electricity, allowing communities greater control over their expenditures (Ezor, 2009).

3. METHODOLOGY

To validate the suitability of the proposal presented by Del-Río-Carazo *et al.* (Del-Río-Carazo, Acquila-Natale, et al., 2022) for configuring management models in rural electrification projects, this study aims to achieve comprehensive coverage of rural electrification case studies through a systematic literature review (SLR). SLRs identify and examine aspects relevant to specific research questions and synthesize search results (Xiao & Watson, 2019). This method is used to discover new practices, identify research gaps, or, as in this research, generate statements to guide decision-making (Munn et al., 2018). The systematic approach of SLRs facilitates replication due to the transparency of the process (Grant & Booth, 2009). Furthermore, SLRs are highly regarded within management research as an appropriate research methodology (Snyder, 2019). Following the methodology outlined in Khan *et al.* (Khan et al., 2003), an SLR entails five stages: (1) formulating the research question, (2) identifying relevant studies, (3) selecting studies, (4) summarizing evidence, and (5) interpreting results. After formulating the research problem, with aims to analyze different management models in rural electrification projects, three specific research questions were defined:

RQ1: Does the model proposed by Del-Río-Carazo *et al.* (2022) cover all the aspects of the management model identified in the case studies?

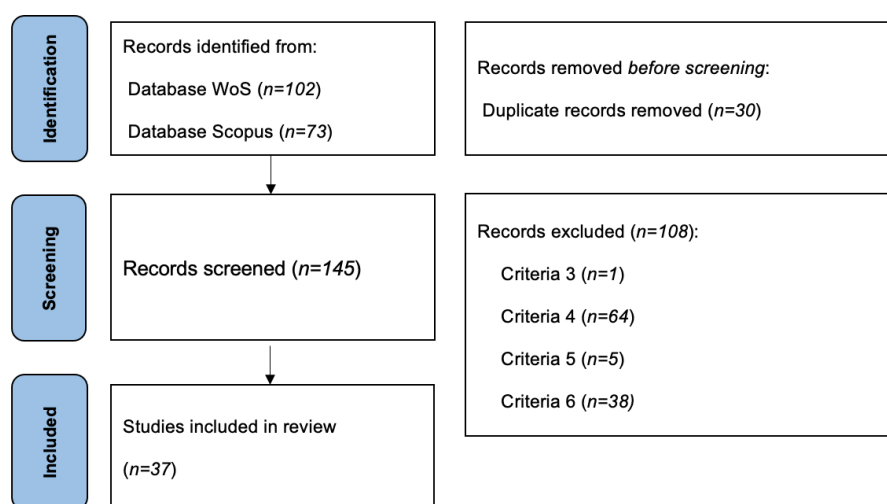
RQ2: Does the analysis of the case studies reveal new dimensions or suggest changes to the model? If so, can the research propose a comprehensive model based on theory and practice?

RQ3: What are the main elements present in the management of rural electrification projects?

To conduct the SLR, records were retrieved from the Web of Science and Scopus databases. Following a preliminary assessment of the initial search query ("rural electrification" AND management AND model), the research team identified numerous documents addressing highly technical aspects of energy operation, distribution, and demand-side management. Consequently, the search query was modified by excluding the term "energy management" due to its technical connotation, which did not align with the objectives of this study. The final query string used for the analysis was "rural electrification" AND management AND model NOT "energy management" in the title, abstract, and keywords. The resulting dataset, combining both databases, included a total of 175 documents.

The screening criteria for the selection process were as follows: (1) publications in English or Spanish (languages in which the research team members are highly proficient); (2) inclusion of case studies on electrification projects in developing countries; and (3) reference to any component of the management model (governance, technology, business model). Case studies published in journals, proceedings, and book chapters were considered suitable for review. At this stage, 30 duplicates were identified and removed. Next, after reviewing titles and abstracts, 77 documents were excluded because for failing to meet the screening criteria. A further full-text review resulted in the exclusion of 33 additional documents. To ensure the integrity of the review process, a co-reviewer evaluated the exclusions, replicating the process and identifying any discrepancies. This process is documented in an Excel file available at [<https://shorturl.at/oCIK7>]. The final dataset comprises 37 documents (acceptance rate of 25.5%). The document selection process (Figure 1) adhered to the PRISMA statement (Page et al., 2021).

Fig. 1. PRISMA flow diagram for article selection (Authors own work)



4. ANALYSIS AND DISCUSSION

The following subsections examine different aspects of the documents in the final sample. A protocol was developed to guide the analysis of the selected articles (Table 1). The analysis includes a bibliometric and a content analysis.

Table 1. Review protocol. Adapted from Mishra, Singh and Koles (Mishra et al., 2021)

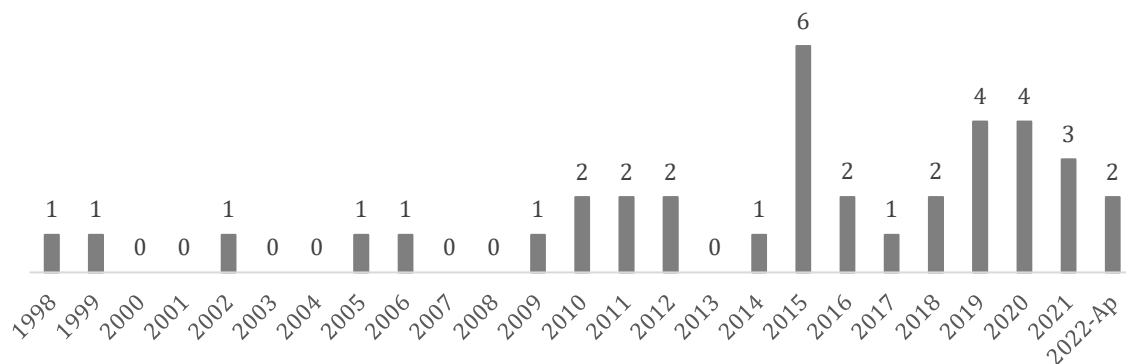
Bibliographic Data	Description
Author(s)	Who is the author?
Type of publication	What type of publication is the paper?
Journal	Which journal was the article published in?
Year of publication	When was the article published?
Origin first author	Where is the first author from?
Number of citations	How many citations does the paper have?
Case study location	Where does the case study take place?
Governance model	What type of governance model is applied in the case study?
Technological model	What type of technological model is applied in the case study?
Business model	What type of business model is applied in the case study?

4.1 Bibliometric analysis

The bibliometric analysis focuses on the year, type, and journal (or conference) of publication, the number of citations of each document, the country of origin of the first author, and the country where the case study takes place. Only the first author was considered due to the frequent presence of co-authors from multiple countries, particularly those where the project is implemented. By focusing on the leading author, the analysis identifies the country of origin of the research study.

At first glance, the number of documents containing cases studies related to the management of rural electrification projects in developing countries has grown significantly since 2015 (Figure 2). Of the 37 selected publications, 22 (59.5%) were published after 2014. This finding underscores the relevance of the topic, aligning with the sustainability policies implemented worldwide following the definition of the SDGs in 2015, where energy plays a fundamental role. The analysis reveals a strong presence in academic journals, with 28 articles (75.7% of the total publications).

Fig. 2. Distribution of documents by year (N=37) (Authors own work)



The largest number of studies was published in the following journals: *Energy*, *Renewable Energy*, *Energy for Sustainable Development* and *Renewable and Sustainable Energy Reviews* (three each, accounting for 10.7% of the total publications). The article with the highest number of citations, *Renewable rural electrification: Sustainability assessment of mini-hybrid off-grid technological systems in the African context* (Brent & Rogers, 2010), received 87 citations in Web of Science and 103 in Scopus. This study analyzed the sustainability of a rural electrification case using microgrids and renewable sources in South Africa, concluding that the project was not viable due to two primary reasons: high system costs and the complexity of the socio-institutional system. The study addresses two of the management dimensions—governance and technology—but omits the business model, which could be essential for addressing the project’s primary failure factor: affordability.

The 37 papers identified a total of 95 case studies from 33 countries, all of which are developing nations, representing 20% of the total. Peru (18 case studies, 18.95% of the total) and India (17 case studies, 17.89% of the total) had the highest number of case studies analyzed. Additionally, the 33 countries included in the analysis display diverse energy access rates compared to the average rate for developing countries, which is 85.72%. Forty-two percent of the countries studied have energy access rates below this average, while 58% exceed it.

4.2 Content analysis and discussion

The content analysis addresses the three research questions and has been carried out in three phases. First, the selected case studies were analyzed based on the proposal by Del-Río-Carazo *et al.* (2022). This phase aimed to validate the model by determining whether all aspects in the model are

reflected in the case studies. Second, the analysis sought to uncover additional configurations not present in the original study that should be incorporated into the model—or identify any necessary modifications. Third, if the results of the first two phases suggested a new conceptualization of the model, the case studies were reanalyzed using the revised model to identify and discuss the most common elements in the configuration of management models for rural electrification projects. While the 95 case studies share common general characteristics as rural electrification projects in developing countries, notable heterogeneity exists in their management approaches. This diversity allows new elements to be extracted throughout the phases, significantly enriching the analysis outcomes and strengthening the theoretical model.

4.2.1 RQ 1. Does the model proposed by Del-Río-Carazo et al. (2022) cover all the aspects of the management model identified in the case studies? Is the model easily understandable?

All 95 cases studies detail, to varying degrees, the technological model (98%), with the two aspects of this dimension—location and source generation—mentioned in most cases (98% and 75%, respectively). The same level of detail is not observed for the other two dimensions: governance and business models. The governance model is specified in 60 case studies (63%), while details about the business model are provided in 58 case studies (61%). The analysis finds no relationship between year of publication and the presence or absence of these dimensions. Figure 3 illustrates the distribution of the first-order components of each dimension covered by the case studies. These results are analyzed and discussed in the following subsections.

Fig. 3. Analysis performed with the model of Del-Río-Carazo, Acquila-Natale, et al. (2022).

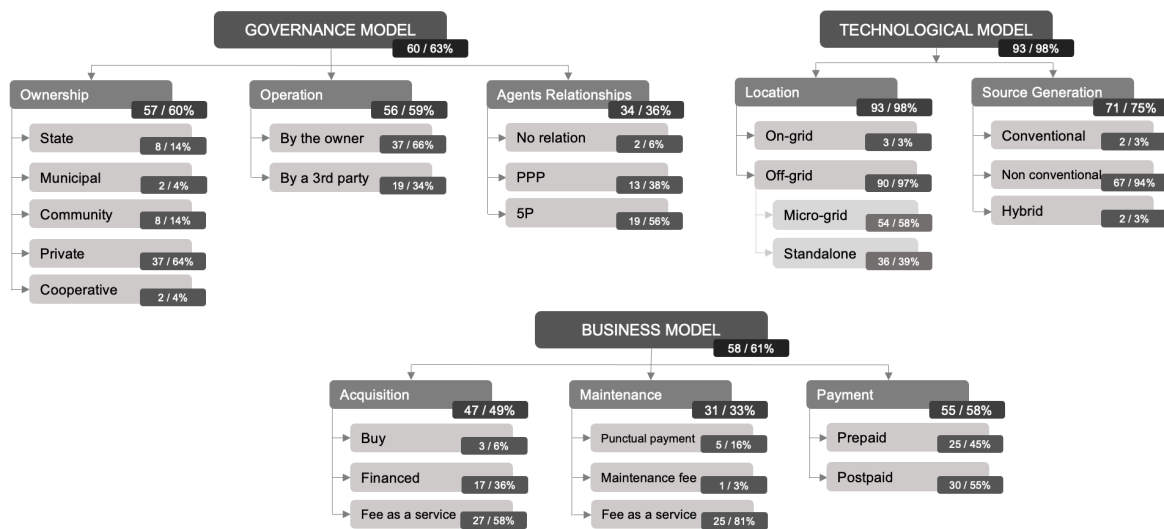


Figure 3 shows that all dimensions and elements appear in at least one case. However, some elements are more prominent than others. The following subsections provide a breakdown of the different elements to assess the adequacy of the model.

4.2.1.1 Governance Model

In the governance model, project ownership and operation are the most frequently mentioned elements in the case studies (60% and 59%, respectively), which highlights the importance of operation and maintenance in managing rural electrification projects. Ownership predominantly features private initiatives (Bandi et al., 2020; Del-Río-Carazo, Acquila-Natale, et al., 2022; Diniz,

1998; Eras-Almeida et al., 2019; Ferrer-Martí et al., 2012; Gözl, 2005; Henshel et al., 2010; Ibrahim et al., 2002; Knuckles, 2016; McLean Slaughter et al., 2016; Wong & Mathur, 2011), which account for more than half of the case studies (64%). These are followed by state-owned and community projects (de Gouvello & Leterme, 1999; Diniz et al., 2006; Ferrer-Martí et al., 2012; Gómez-Hernández et al., 2019; León et al., 2020; Sampath Kumar et al., 2018) (14% and 14%, respectively). This result is unsurprising, as these entities typically have the financial and human resources required to execute such projects.

In terms of operation, there is a balance between owner-operated projects (Bandi et al., 2020; Bhandari et al., 2018; Bueno-Lopez et al., 2019; de Gouvello & Leterme, 1999; Del-Río-Carazo, Acquila-Natale, et al., 2022; Diniz, 1998; Diniz et al., 2006; Eras-Almeida et al., 2019; Gözl, 2005; Gómez-Hernández et al., 2019; Henshel et al., 2010; Ibrahim et al., 2002; Katre et al., 2019; Knuckles, 2016; Mohns & Stein, 2008; Pinheiro et al., 2011, 2012) and third-party-operated projects (Del-Río-Carazo, Acquila-Natale, et al., 2022; Diniz et al., 2006; Eras-Almeida et al., 2019; Ferrer-Martí et al., 2012; Gómez-Hernández et al., 2019; Juanpera et al., 2021; Knuckles, 2016; León et al., 2020; Lillo, Ferrer-Martí, Boni, et al., 2015; Lillo, Ferrer-Martí, Fernández-Baldor, et al., 2015; Pinheiro et al., 2012; Sampath Kumar et al., 2018; Wong & Mathur, 2011), with a slight preference for owner-operated projects (66%). This aligns with the predominance of private projects, as private promoters typically possess the resources to promote the project *and* the knowledge and expertise, which may be lacking in other types of ownership.

Finally, the results show that 5P initiatives are booming and are becoming the most popular form of relationship. When observing the temporal trend, a pattern is observed where initially the projects involved no relationships between agents (Bueno-Lopez et al., 2019; Mohns & Stein, 2008) (6%), gradually transitioning toward PPP (Bhandari et al., 2018; Brent & Rogers, 2010; Diniz, 1998; Diniz et al., 2006; Gözl, 2005; Gómez-Hernández et al., 2019; Henshel et al., 2010; Ibrahim et al., 2002; Pinheiro et al., 2011, 2012; Sampath Kumar et al., 2018) (38%) and 5P (Bandi et al., 2020; de Gouvello & Leterme, 1999; Del-Río-Carazo, Acquila-Natale, et al., 2022; Eras-Almeida et al., 2019; Ferrer-Martí et al., 2012; Katre et al., 2019; Lillo, Ferrer-Martí, Boni, et al., 2015; Lillo, Ferrer-Martí, Fernández-Baldor, et al., 2015; Mainali & Dhital, 2015; Wong & Mathur, 2011; Zimmerle et al., 2020) (56%) models.

4.2.1.2 Technological Model

In the technological model, all case studies cover location, and most also mention source generation. Regarding location, the predominant configurations are off-grid (97%)—only Gómez-Hernández *et al.* (Gómez-Hernández et al., 2019) and León *et al.* (León et al., 2020) address on-grid configurations—, with a balanced distribution between micro-grid and standalone setups. As expected, micro-grids are primarily used in communities with low dispersion (Bae et al., 2021; Bertheau, 2020; Bhandari et al., 2018; Brent & Rogers, 2010; Bueno-Lopez et al., 2019; Del-Río-Carazo, Acquila-Natale, et al., 2022; Diniz et al., 2006; Gözl, 2005; Gómez-Hernández et al., 2019; Ibrahim et al., 2002; Katre et al., 2019; Knuckles, 2016; Konneh et al., 2022; Lillo, Ferrer-Martí, Fernández-Baldor, et al., 2015; Lillo, Ferrer-Martí, Boni, et al., 2015; Mainali & Dhital, 2015; Mohns & Stein, 2008; Pinheiro et al., 2011, 2012; Sampath Kumar et al., 2018; Terrapon-Pfaff et al., 2014; Wang et al., 2021; Zimmerle et al., 2020), while standalone configurations are used in isolated households (Bandi et al., 2020; de Gouvello & Leterme, 1999; Del-Río-Carazo, Acquila-Natale, et al., 2022; Diniz, 1998; Eras-Almeida et al., 2019; Ferrer-Martí et al., 2012; Gómez-Hernández et al., 2019; Henshel et al., 2010; Juanpera et al., 2021; León et al., 2020; McLean Slaughter et al., 2016; Ranaboldo et al., 2015; Sampath Kumar et al., 2018; Terrapon-Pfaff et al., 2014; Wong & Mathur, 2011).

In terms of source generation, there is a dominance of non-conventional renewable energy sources (Bandi et al., 2020; Bertheau, 2020; Bhandari et al., 2018; Brent & Rogers, 2010; Bueno-

Lopez et al., 2019; de Gouvello & Leterme, 1999; Del-Río-Carazo, Acquila-Natale, et al., 2022; Diniz, 1998; Diniz et al., 2006; Eras-Almeida et al., 2019; Ferrer-Martí et al., 2012; Gómez-Hernández et al., 2019; Henshel et al., 2010; Ibrahim et al., 2002; Juanpera et al., 2021; Katre et al., 2019; León et al., 2020; Lillo, Ferrer-Martí, Fernández-Baldor, et al., 2015; Lillo, Ferrer-Martí, Boni, et al., 2015; Loayza, 2015; McLean Slougher et al., 2016; Mohns & Stein, 2008; Pinheiro et al., 2011, 2012; Rajanna & Saini, 2017; Ranaboldo et al., 2015; Sampath Kumar et al., 2018; Terrapon-Pfaff et al., 2014; Wang et al., 2021; Wong & Mathur, 2011; Zimmerle et al., 2020) (94%) versus the lesser used conventional (Gómez-Hernández et al., 2019; León et al., 2020) (3%) and hybrid (Konneh et al., 2022; Mainali & Dhital, 2015) (3%).

4.2.1.3 Business Model

Finally, in the business model dimension, affordability remains one of the major challenges for rural electrification projects (Knuckles, 2016). The analysis highlights an active effort to design business models that allow users to afford the cost of energy access without compromising the income required for other universal basic services (Ferrer-Martí et al., 2012; Gómez-Hernández et al., 2019). An analysis of business model elements reveals that fee-as-a-service is the dominant option for acquisition (Bhandari et al., 2018; de Gouvello & Leterme, 1999; Del-Río-Carazo, Acquila-Natale, et al., 2022; Diniz, 1998; Eras-Almeida et al., 2019; Ferrer-Martí et al., 2012; Gómez-Hernández et al., 2019; Henshel et al., 2010; Ibrahim et al., 2002; Juanpera et al., 2021; Katre et al., 2019; Knuckles, 2016; Lillo, Ferrer-Martí, Boni, et al., 2015; Lillo, Ferrer-Martí, Fernández-Baldor, et al., 2015; Loayza, 2015; Mohns & Stein, 2008; Ranaboldo et al., 2015; Sampath Kumar et al., 2018; Wong & Mathur, 2011) (58%). This model is preferred over buy (Del-Río-Carazo, Acquila-Natale, et al., 2022; Eras-Almeida et al., 2019) and financed (Bueno-Lopez et al., 2019; Del-Río-Carazo, Acquila-Natale, et al., 2022; Eras-Almeida et al., 2019; Lillo, Ferrer-Martí, Boni, et al., 2015) acquisition, as fee-as-a-service allows users to plan expenses over time in manageable amounts, avoiding the burden of a high one-time investment required to purchasing equipment outright.

Maintenance is critical to ensuring the sustainability of interventions. The few cases that cover failed projects identify costs and affordability as the most important reasons for failure (Mohns & Stein, 2008; Zimmerle et al., 2020) (33%). Therefore, it is essential to ensure that users can afford repair and maintenance costs to sustain the project over time. Fee-as-a-service maintenance (Bhandari et al., 2018; de Gouvello & Leterme, 1999; Del-Río-Carazo, Acquila-Natale, et al., 2022; Diniz, 1998; Domenech et al., 2015; Eras-Almeida et al., 2019; Ferrer-Martí et al., 2012; Gómez-Hernández et al., 2019; Henshel et al., 2010; Ibrahim et al., 2002; Juanpera et al., 2021; Katre et al., 2019; Lillo, Ferrer-Martí, Boni, et al., 2015; Lillo, Ferrer-Martí, Fernández-Baldor, et al., 2015; Loayza, 2015; Sampath Kumar et al., 2018; Wong & Mathur, 2011) is the most common approach, aligning with its for acquisition purposes (81%).

Finally, regarding payment, postpaid options (Bhandari et al., 2018; Del-Río-Carazo, Acquila-Natale, et al., 2022; Domenech et al., 2015; Eras-Almeida et al., 2019; Ferrer-Martí et al., 2012; Gómez-Hernández et al., 2019; Ibrahim et al., 2002; Katre et al., 2019; Knuckles, 2016; Lillo, Ferrer-Martí, Fernández-Baldor, et al., 2015; Lillo, Ferrer-Martí, Boni, et al., 2015; Sampath Kumar et al., 2018) (55%) appear to be preferred over prepayments (Bueno-Lopez et al., 2019; de Gouvello & Leterme, 1999; Eras-Almeida et al., 2019; Ferrer-Martí et al., 2012; Henshel et al., 2010; Knuckles, 2016; Lillo, Ferrer-Martí, Boni, et al., 2015; Lillo, Ferrer-Martí, Fernández-Baldor, et al., 2015; McLean Slougher et al., 2016; Wong & Mathur, 2011) (45%). A possible reason is that post-payment is easier to implement for owners, as it requires less technological development, even though it may be less favorable for users. The following subsections propose more user-friendly solutions for payment.

From this initial analysis, we conclude that (a) all aspects and configurations included in the model are relevant and should be retained; (b) some concepts require revision or expansion to better

reflect real project implementations; and (c) while the technological and governance models in the original framework are easily understood, the business model requires a more detailed review of its elements and configurations.

4.2.2 RQ2: Does the analysis of the case studies reveal new dimensions or suggest changes to the model? If so, can the research propose a comprehensive model based on theory and practice?

The analysis of the configurations of management models in the case studies reveals new elements and additional configurations that should be incorporated into the model to provide a more comprehensive understanding of real rural electrification projects.

4.2.2.1 Governance Model

In terms of governance, the results suggest that the concept of ownership requires further refinement. While resources are generally provided by private entities and states, communities and municipalities also play significant roles in the governance of these interventions. Therefore, a distinction is proposed between project promoters and owners. Promoters are the primary drivers of the intervention, typically responsible for funding the project and selecting the location for its implementation. Owners, by contrast, assume leadership of the project, either partially (as owners of the systems) or entirely (as owners of the project).

The analysis indicates that states and private entities often act as promoters, while ownership of the systems (and sometimes of the entire project) can be transferred to local agents, either at the community or individual level (Ferrer-Martí et al., 2012; Pinheiro et al., 2011). This transfer is more common in microgrid systems, which are typically promoted and financed by private or state entities. Once the project is planned, ownership is transferred to the community, which then assumes responsibility for its maintenance and management, gaining full decision-making capacity. Examples of transferred ownership include Gómez-Hernández *et al.* (Gómez-Hernández et al., 2019), where the community decided to provide users with free use and low maintenance rates (\$1), or Bueno-Lopez *et al.* (Bueno-Lopez et al., 2019), where the community allocated profits generated from the productive use of the energy (e.g., cooling water and beverages) to cover system maintenance expenses. According to Mohns and Stein (Mohns & Stein, 2008), granting the community control of the project directly impacts the sustainability of the intervention, as sustainability depends on both the resources used and effective management.

The operation element presents the same challenge as ownership; the original proposal encompasses too many tasks, making it difficult to distinguish the responsibilities of each (Zimmerle et al., 2020). Accordingly, based on observations from various cases, we propose separating operation into three distinct components to reflect the specific tasks and responsibilities: maintenance, charging, and payment management, each requiring different skills for execution (Wong & Mathur, 2011). These tasks may fall under the responsibility of promoters or other actors. For example, the entity responsible for maintenance must have specialized training on the equipment, knowledge of battery tests to perform during failures, and adequate technical tools for system repair (Zimmerle et al., 2020). Equipment charging can be carried out by users, households, community centers, or third-party agents who charge systems on a large scale. For instance, Mohns and Stein (Mohns & Stein, 2008) describe solar lanterns recharged at a community kiosk. Finally, payment management involves fee collection and monitoring whether users remain up to date with their payments. In highly isolated communities, where it is impractical for users to travel to pay installments, the agent responsible for payments collects all fees from the community and travels to the designated payment point (Del-Río-Carazo, Acquila-Natale, et al., 2022).

Considering the above, the proposed governance model includes the following elements: *Promoters, Ownership, Maintenance, Recharging, Payment management and Relationships between*

agents. Each of these components plays a distinct role in the configuration of the governance model. *Promoters* are the entities initiating and financing the project. *Ownership* refers to the agents that assume control of the infrastructure and its long-term management. *Maintenance* identifies who is responsible for system repairs. *Recharging* specifies how and where energy storage devices are replenished. *Payment management* addresses fee collection and financial monitoring. Lastly, *Relationships between agents* describes how stakeholders—e.g., public, private, community—interact and collaborate to sustain the intervention.

4.2.2.2 Technological Model

From the analysis of the technological model, an additional type of off-grid configuration was identified, positioned between mini-grids and isolated home systems: nano-grids. Nano-grids are independent electricity grids at the home or building level, characterized by a shorter scope and smaller size micro-grids (Bae et al., 2021). Additionally, the analysis of the case studies suggests incorporating into the model the type of energy usage (McLean Slougher et al., 2016), distinguishing between instances where the power is used solely for lighting and those where users connect household appliances. In the former scenario, devices must operate in direct current (DC) or alternating current (AC), whereas the latter case requires either AC or DC devices plus an inverter (Lillo, Ferrer-Martí, Boni, et al., 2015; Sampath Kumar et al., 2018).

With these modifications, the proposed technological model includes *System type*, *Source generation*, and *Output*. *System type* distinguishes between micro-grids, standalone systems, and nano-grids, depending on the number of users and degree of interconnection. *Source generation* indicates the type of energy used—conventional, renewable, or hybrid. Finally, *Output* refers to the nature of the electric current (AC/DC) and the end-use applications, such as lighting or powering household appliances.

4.2.2.3 Business Model

Finally, as mentioned earlier, it is necessary to review the business model dimension. The analysis of the case studies suggests that a sequential process encompassing the different stages of the sales process may be more appropriate for analyzing this dimension. The following subsections detail the elements of the new proposal, adopting this perspective.

In the first stage, acquisition, the analysis identifies two modes of purchase: systems are either purchased—in cash or financed through a grant, subsidy or a microfinance entity (Bueno-Lopez et al., 2019)—or rented, with or without subsidy. In the latter case, a deposit may be required to cover potential damages to the system (de Gouvello & Leterme, 1999; McLean Slougher et al., 2016). Notably, no cases were observed where renting was combined with financing. Once the equipment is purchased, the project must ensure that the system is repaired in case of failures; otherwise, the project risks failure (Zimmerle et al., 2020). For maintenance, options include one-time user payments upon equipment failure (McLean Slougher et al., 2016), or periodic fees to cover repairs or system replacements when they reach the end of their service life (Domenech et al., 2015; Gómez-Hernández et al., 2019).

In addition to the two payment types included in the original proposal (prepaid and postpaid), the analysis suggests adding an additional component: rate. This differentiates between fixed and variable tariffs based on consumption. Hybrid modalities—combining a fixed component, typically for maintenance, with a variable component for energy consumption—were also observed in some cases, especially in micro-grids, where monitoring energy consumption at the individual level is feasible (Domenech et al., 2015).

The analysis suggests adding two new elements to the business model: payment methods and contract cancellation. Regarding payment methods, two main options are considered. Although cash is always used in the cases studied, one of the primary challenges for these projects is the management

of fee collection. To address this problem, a potential solution—though not directly observed in the case studies—is the digitization of payments. Notably, while digital payments have yet to become widespread, mobile payment pilots are underway to explore this option (Telles & Waldron, 2017). These pilot projects have been enabled by increased connectivity in rural areas of developing countries in recent years, with network access rising from 44.4% of the population in 2019 to 57% in 2021 (Statista, 2022). Improved infrastructure means that more people in rural areas of developing countries now have internet access points in or near their communities. In this digital context, rural electrification projects have the opportunity to adopt digital payments as a new method for collecting electrification tariffs (Baker, 2022).

Finally, regarding contract cancellation, the reasons for termination are often unspecified in the cases studied, which could jeopardize the long-term sustainability of the project. Potential risks include payment delays or improper use of the equipment. However, some cases detail strategies to mitigate these risks, such as including cancellation clauses for non-payment within a specific timeframe or for system misuse (Katre et al., 2019).

After this review, the business model dimension includes the following elements: *Acquisition*, *Maintenance*, *Rate*, *Payment type*, *Payment method*, and *Cancellation*. *Acquisition* refers to whether the energy system is purchased, financed, or rented. *Maintenance* captures how system repairs and replacements are handled—either through periodic fees or on-demand payments. *Rate* differentiates between fixed tariffs—constant cost regardless of consumption—and variable tariffs—dependent on usage. *Payment type* indicates whether users pay before consuming energy (prepaid) or afterward (postpaid). *Payment method* identifies how the transaction is executed—e.g., in cash or digitally. Lastly, *Cancellation* addresses the conditions under which the service contract may be terminated, such as prolonged non-payment or equipment misuse

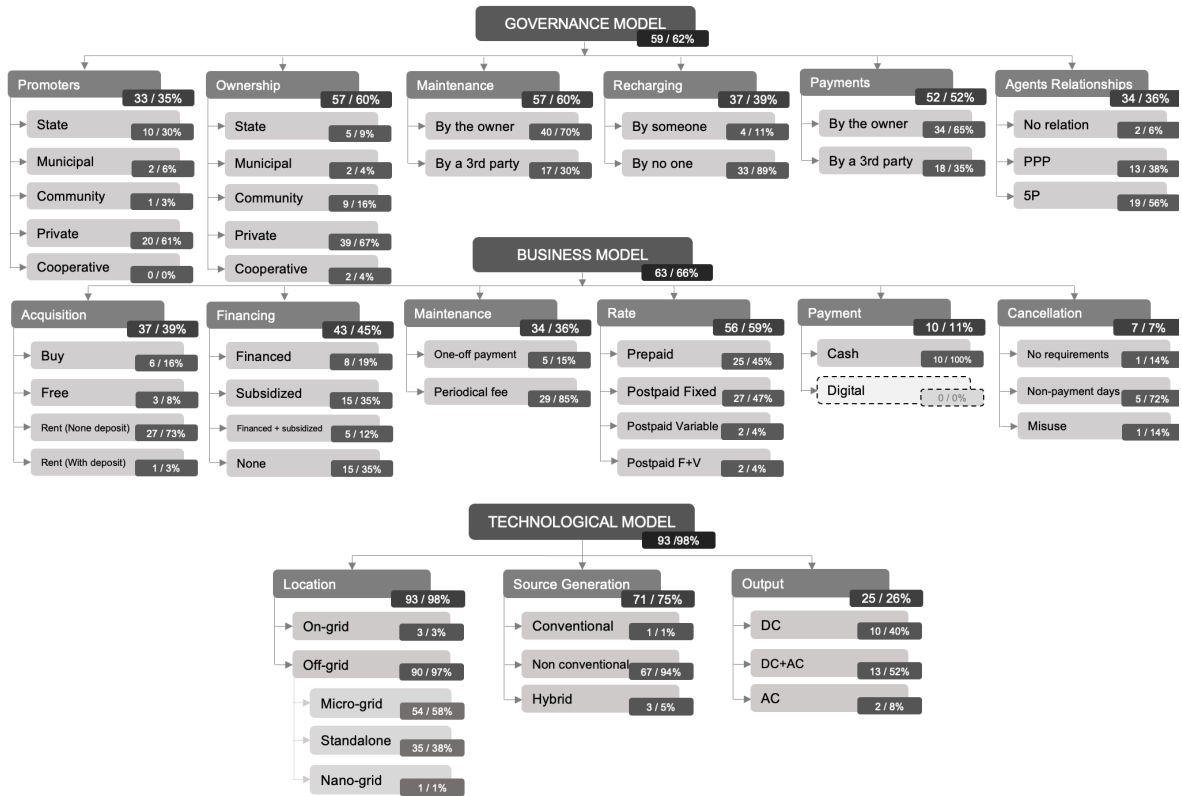
As a result of this second analysis, we conclude that: (a) no new dimensions needed to be incorporated into the model; (b) seven new components were added to make the model more comprehensive and easier to understand; (c) providing a more comprehensive model increases complexity: the new model includes 47 elements, almost the double of elements present in the original model (27).

4.2.3 RQ3: What are the main elements present in the management of rural electrification projects?

After reviewing and improving the model in Del-Río-Carazo *et al.* (2022), the case studies were analyzed using the revised model, which is summarized in Figure 4. Although the revised model includes more components (47 compared to 27), this increase is based on recurring patterns identified across the 95 case studies. The additional elements reflect specific aspects of project implementation—such as payment mechanisms and maintenance responsibilities—that were not fully addressed in the original model. Their inclusion makes the model more representative of real-world configurations, without adding unnecessary complexity.

The following subsections detail and discuss the results of this analysis. It is important to note that the analysis is descriptive and does not explore the influence of each configuration on project success, as most of the research studies do not specify whether the projects were successful.

Fig. 4. Analysis performed with the revised management model (Authors own work)



4.2.3.1 Governance Model

In the governance model, predominant configurations are observed in several components. While private (61%) and state (30%) are most notable at the promoter level, the analysis indicates that in ownership is sometimes transferred to other agents, such as communities (16%) and cooperatives (4%). States tend to transfer project leadership, whereas private initiatives are more likely to retain it. This may suggest that state promoters either recognize the importance of community involvement or lack the capacity to manage operations and maintenance, prompting the transfer of responsibility. Regardless, combining private or state promoters with community ownership leverages the financial and technical resources of states and private entities alongside the local knowledge of community needs and characteristics. Importantly, transferring leadership or ownership does not mean abandoning the project. For instance, in Pinheiro *et al.* (Pinheiro et al., 2012), a power plant's ownership was transferred to a community cooperative, but the state continued to provide technical support and monitoring to prevent failures during the initial years of operation.

Regarding operation and maintenance, maintenance is typically handled by the same agent responsible for managing payments, often the owners (maintenance: 70%; payments: 55%). Charging is mentioned less frequently and usually does not require human intervention (89%), as most systems are charged autonomously in households. The need for manual charging arises in only four case studies, where solar lanterns are recharged at kiosks near the communities. Similar to charging, bringing payment and maintenance points closer to communities would be a practical approach, even if it requires training community members to perform these tasks. This approach offers two key benefits: smoother operations and the transfer of skills and knowledge to the community (International Renewable Energy Agency (IRENA), 2021).

Finally, as observed in the original analysis, projects typically involve multiple agents (PPP, 38%; 5P, 56%). This approach can provide more integrative solutions tailored to the needs of the area by leveraging the expertise of various agents at different levels.

4.2.3.2 Technological Model

In the technological model, the results align with those of the original analysis, as the model remains largely unchanged in this dimension. Predominant configurations include off-grid solutions, evenly distributed between microgrids (57%) and standalone systems (39%). Both configurations are well suited for rural electrification projects and are typically implemented with non-conventional generation sources (94%), with a growing trend to hybrid sources (5%) in microgrids. Hybrid systems are favored due to challenges associated with battery usage, as batteries are both a polluting element in off-grid systems and difficult to recycle (Mrozik et al., 2021). Regarding output, there is a preference for AC (60%) over DC (40%), regardless of the year of research. This preference for AC reflects community needs for both lighting and electricity, requiring generation equipment (e.g., solar panels) large enough to meet household demand.

4.2.3.3 Business Model

The analysis of the business model reveals findings not observed in the previous analysis, supporting the superiority of the revised model. Fee-as-a-service emerges as the preferred acquisition mode (76%) because it enables communities to avoid initial outlays and to spread the cost of access over time, aiding household economic management. Notably, the acquisition mode is frequently subsidized (81% of fee-as-a-service models are subsidized), representing an additional income source and facilitating the intervention's economic sustainability without imposing a financial burden on clients (Independent Evaluation Group World Bank, 2008). In cases where systems were purchased (16%), the acquisition was always financed, indicating the difficulty for households to bear the total cost of equipment upfront.

The analysis of the business model for maintenance shows that the most common method is fee-as-a-service (85%). Additionally, all cases where maintenance involves a one-off payment (15%) include purchasing the equipment. The rarer cases of free acquisition include periodical fee maintenance models, which appear reasonable to ensure project continuity. The results highlight the emphasis of these projects on affordability—not only for acquisition but also for system maintenance. As noted earlier, affordability is often the primary reason for the failure of rural electrification projects (Gölz, 2005).

When payments are made periodically (fee-as-a-service or financed purchase), fixed tariffs dominate (92%), while variable tariffs are less common (8%). This preference may stem from the ease of managing fixed tariffs, as variable tariffs based on consumption require technology to monitor system usage, transmit data, and process calculations for each household. A similar technological complexity likely contributes to the predominance of postpaid tariffs (55%), where individuals pay installments after consuming energy. This option, however, may reduce households control since it precludes buying energy in advance and often results in debt to electricity companies (Dakpogan & Ellington, 2022). Pay-as-you-go solutions are emerging to address this issue, allowing users to prepay for electricity and consume it until the purchased amount is exhausted. Pay-as-you-go also lowers the risk of default due to non-payment (IRENA, 2020).

In all cases, payments are made in cash (100%). However, as mentioned earlier, trends in rural electrification suggest a shift toward digitalizing payment processes. Regarding contract cancellation, this is addressed in only a small number of cases (7%), with non-payment over a specified period being the most common reason (72%). Future projects should carefully consider contract cancellations, as systems may need to be relocated to households or locations where they can be utilized more effectively in cases of misuse by the original beneficiaries (Katre et al., 2019).

In summary, the configuration choices for management models in rural electrification projects typically focus on ensuring the affordability and sustainability of these initiatives. While state and private resources predominate, projects also aim to involve communities actively in their design and

development, alongside the participation of multiple institutions, such as academic or non-profit organizations, in the form of 5P collaborations. The collaboration of all parties throughout project development enhances sustainability, positively impacts communities, and improves management processes through investments in human and technological resources that support optimal intervention outcomes. At the technological level, off-grid solutions utilizing non-conventional resources are prevalent, ensuring both environmental sustainability and economic viability. The analysis shows that households require energy for lighting, as well as for more power-intensive uses. Additionally, several business model configurations aim to ensure affordability; among these, fee-as-a-service models predominate for both acquisition and maintenance, as they enable households to meet costs periodically with smaller financial commitments. These models are often subsidized, unlike purchase-based models. Finally, while some decisions—such as digital payments or prepaid tariffs—are less common due to current technological barriers, they hold promise for improving rural electrification projects in the future.

5. CONCLUSIONS

5.1 Recommendations

This study provides significant implications and recommendations for project developers, managers, academia, and public institutions involved in rural electrification projects. For project managers, the comprehensive management framework consolidates potential configurations into a single model, offering a clear reference for designing effective projects. By systematically evaluating governance, technology, and business dimensions, managers can explore innovative configurations, improve decision-making processes, and address challenges such as affordability and sustainability. For example, adopting fee-as-a-service models enables households to manage access costs more effectively, while state subsidies enhance project affordability.

For public institutions and policymakers, the findings highlight the importance of community participation at all stages of rural electrification projects. Involving local communities in design, implementation, and maintenance ensures that solutions are tailored to specific needs, thereby increasing project acceptance and sustainability. The integration of multiple agents, such as state entities and universities, optimizes resource use and improves intervention quality. Policies promoting collaborative approaches—such as 5P models—can magnify the socio-economic impact of these initiatives.

For academia, this research advances theoretical understanding by integrating governance, technology, and business perspectives into a unified framework. The expanded model, which incorporates new dimensions and configurations, establishes a foundation for further research and bridges the gap between theoretical studies and practical applications. Future studies could build on these findings to examine the long-term evolution of rural electrification management, especially in light of emerging trends like digital payment systems and battery recycling.

By addressing these diverse perspectives, the study deepens theoretical knowledge and offers practical tools for designing and implementing sustainable rural electrification projects. The revised model extends the original version by incorporating a wider range of configurations observed across 95 case studies, compared to the three used in the initial framework. The additional components—such as rate structures, payment methods, and contract cancellation—address specific implementation issues related to affordability, payment collection, and long-term project viability. These aspects were not captured in the original model but are common in the cases analyzed. Their inclusion provides a more accurate representation of current practices and offers practical value for designing and

managing rural electrification projects. Although the model is more detailed, this increase reflects real-world complexity and improves its relevance for applied use.

5.2 Conclusions

This study comprehensively investigates management models employed over recent decades in rural electrification projects in developing countries. Building on an existing framework for rural electrification project management, this research identifies new dimensions and integrates them into a comprehensive model grounded in theoretical constructs and practical insights from an in-depth analysis of 95 case studies. The model's various configurations are meticulously examined, offering valuable insights into prevalent practices in the field.

At the theoretical level, several important conclusions have emerged: (1) the management of rural electrification projects is consistently linked, in most cases examined, to the sustainability of interventions; (2) these projects can be categorized into three primary dimensions; governance, technology, and business. This framework highlights critical areas requiring focused attention during project conception and execution; (3) while theoretical studies on rural electrification management provide foundational knowledge and identify prevalent configurations, they often fail to capture the nuanced realities encountered in practical, real-world projects.

On a practical level, this research expands previous management models, doubling the number of included configurations. It offers a more comprehensive view of intervention realities and provides a valuable reference for future project promoters.

From the second part of this research, the following conclusions are highlighted. First, affordability and sustainability remain the primary challenges for interventions. Achieving access in remote areas is insufficient; such access must align with SDG goals. Second, at the governance level, active community participation throughout the entire process—from design to implementation—facilitates sustainable solutions with a positive impact on communities. Furthermore, the involvement of other agents, such as universities and local or state entities, optimizes resource utilization and enhances the quality of interventions. Third, at the technological level, the suitability of off-grid solutions combined with non-conventional generation sources is evident, as they ensure environmental sustainability and economic viability. Finally, at the business level, fee-as-a-service models predominate. These configurations allow users to incorporate access costs into household budgets through small periodic fees and frequently benefit from state subsidies, providing affordable access to communities.

5.3 Limitations and future research directions

The limitations of this research focus on three key aspects. First, case selection was constrained by the availability and accessibility of data in the existing literature. This limitation may have excluded some relevant or emerging management models, reducing the generalizability of the findings. Second, not all 95 cases provided complete information on each element of the proposed framework, restricting the ability to fully analyze the exact presence of these elements in every case. Finally, this study represents a “snapshot” in time, as the data reflect the status of the projects at the time of publication. This limits the analysis of long-term evolution and the sustainability of these projects.

The proposed directions for future research aim to address these limitations. First, expanding the dataset to include new cases and explore less-documented configurations is recommended to achieve a more comprehensive understanding. Second, conducting sustainability assessments using quantitative scales and adopting a longitudinal approach would allow for the observation of sustainability trends and their interactions with management aspects and practices over time. Finally,

the model should evolve to account for emerging factors, such as advances in ICT and battery recycling, which will significantly influence the management and sustainability of these projects.

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