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Laura Marcela Hinestroza Olascuaga

Supervisor: Doctor Célia Maria Santos Cardoso de Jesus
Co-Supervisor: Doctor Pedro Manuel Santos de Carvalho

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Engineering and Public Policy

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Resumo

Proporcionar um acesso energético fiável a comunidades remotas e rurais é uma condição necessária para promover o desenvolvimento social e económico. Infelizmente, há cerca de 759 milhões de pessoas em todo o mundo que ainda não têm esse serviço básico (em 2019) e cerca de 53% delas vivem na África Subsaariana. Esse cenário também se repete na América do Sul, onde o maior déficit ainda está presente em áreas rurais, em países como Bolívia, Colômbia e Peru, onde as taxas de acesso à eletricidade rural estão abaixo de 90% (em 2019). Alcançar o acesso universal requer um planeamento energético integrado que facilite a concepção e operação sustentáveis de projetos de eletrificação rural a longo prazo.

Tradicionalmente, o conceito de sustentabilidade está associado ao quadro de resultados triplos (TBL), composto por três dimensões-chave ou princípios de sustentabilidade: social, ambiental e económico. No entanto, o trabalho apresentado nesta tese pretende captar outras perspectivas que afetam a sustentabilidade de projetos de eletrificação rural, além da abordagem TBL. Esta tese de doutorado se preocupa em apoiar o planeamento da eletrificação rural nos países em desenvolvimento, contabilizando não apenas os aspectos técnicos, mas também as dimensões social, económica, financeira, comercial, ambiental, política e cultural. Ao fazê-lo, esta tese engloba os estudos de caso da Bolívia, Peru e Colômbia para destacar a importância de interações coordenadas entre os principais interessados, a saber, o governo, formuladores de políticas, fornecedores de energia, investidores privados, doadores e instituições de financiamento. Usando uma abordagem de pesquisa de métodos mistos, que combina análise qualitativa e quantitativa, esta tese de doutoramento estuda a validade e as limitações de diferentes métodos que suportam o planejamento de eletrificação rural, baseado na combinação de abordagens qualitativas e quantitativas.

Principais contribuições são derivadas da resposta a quatro perguntas de pesquisa: A primeira diz respeito a explorar se os programas atuais de eletrificação estão atingindo os domicílios rurais mais pobres. O segundo investiga os principais fatores que determinam a sustentabilidade a longo prazo de projetos de eletrificação fora da rede em comunidades rurais e remotas. O terceiro envolve a identificação dos maiores fatores de risco em projetos de eletrificação fora da rede. Finalmente, a quarta questão analisa o papel das principais partes interessadas na abordagem dos principais desafios nos esforços de eletrificação rural e, assim, alcançar as comunidades da última milha.

As principais contribuições desta tese referem-se a: (i) Primeiramente, utilizar indicadores socioeconómicos complementares, como o Índice de Pobreza Multidimensional, poderia complementar as Necessidades Básicas Insatisfeitas tradicionais (UBN) por capturar informações mais relevantes que poderiam levar a medições mais precisas da pobreza e intervenções de eletrificação rural, não apenas na Bolívia, mas também na Colômbia; (2) Em segundo lugar, este estudo integra duas dimensões adicionais de sustentabilidade ao quadro TBL, nomeadamente os critérios técnicos e comerciais, através da implementação da Medição da Atratividade por uma Técnica de Avaliação Baseada em Categorias (MACBETH); (3) Em terceiro lugar, implementa uma técnica de fluxo de caixa de desconto estocástico combinada com simulação de Monte Carlo para incorporar as principais incertezas e quantificar os riscos de negócios e investimentos associados a um projeto fotovoltaico fora da rede, e (4) O conceito de avaliação de sustentabilidade para seleção de locais foi considerado estimando-se uma pontuação composta que agrupa cada alternativa considerando três categorias possíveis de sustentabilidade: Altamente sustentável, Sustentável e Insustentável.

Com base nessas contribuições, esta tese propõe um conjunto de ideias para a formulação de políticas focadas na integração e ampliação de sistemas baseados em energia renovável sustentável em áreas não eleitas de países em desenvolvimento. Esta tese pode oferecer algum direcionamento para desenvolvedores de projetos e potenciais investidores dispostos a realizar avaliações de sustentabilidade no setor de eletrificação rural.

Palavras-chave: acesso à eletricidade; avaliação de sustentabilidade; desenvolvimento sustentável; eletrificação rural; planeamento de redes isoladas; política energética; sistemas de energia isolados.

Abstract

Providing reliable energy access to remote and rural communities is a necessary condition for fostering social and economic development. Unfortunately, there are about 759 million people across the globe who still lack this basic service (as of 2019) and about 53% of them live in Sub-Saharan Africa. This scenario also replicates in South America, where the highest deficit is still present in rural areas, namely in countries such as Bolivia, Colombia, and Peru, where rural electricity access rates are below 90% (as of 2019). Achieving universal access requires an integrated energy planning that facilitates the sustainable design and operation of rural electrification projects over the long term.

Traditionally, the concept of sustainability is associated with the triple bottom line (TBL) framework, composed of three key dimensions or principles of sustainability: social, environmental, and economic. However, the work presented in this thesis intends to capture other perspectives that affect the sustainability of rural electrification projects, beyond the TBL approach. This doctorate thesis is concerned with supporting rural electrification planning in developing countries by accounting not only for technical aspects, but also for social, economic, financial, commercial, environmental, policy, and cultural dimensions. In doing so, this thesis encompasses the case studies of Bolivia, Peru, and Colombia to highlight the importance of coordinated interactions between key stakeholders, namely, the government, policymakers, energy providers, private investors, donors, and financing institutions. Using a mixed methods research approach, which combines qualitative and quantitative analysis, this doctorate thesis studies the validity and limitations of different methods that support rural electrification planning, based on the combination of both qualitative and quantitative approaches. To address this objective, this thesis focuses on four research questions: The first one concerns exploring whether current electrification programs are reaching the poorest rural households. The second one investigates the key factors that determine the long-term sustainability of off-grid electrification projects in rural and remote communities. The third one involves identifying the biggest drivers of risk in off-grid electrification projects. Finally, the fourth question analyses the role of key stakeholders in addressing the main challenges in rural electrification efforts and thus reaching the last mile communities.

The main contributions derived from this thesis refers to: (i) First, using complementary socio-economic indicators, such as the Multidimensional poverty index could complement the traditional Unsatisfied Basic Needs (UBN) index by capturing more relevant information that could lead to more accurate poverty measurements and rural electrification interventions, not only in Bolivia but also in Colombia; (2) Second, this study integrates two additional sustainability dimensions to the TBL framework, namely the technical and commercial criteria, by implementing the Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH); (3) Third, it implements a stochastic discount cash flow technique combined with Monte Carlo simulation to incorporate key uncertainties and quantify the business and investment risks associated with an off-grid solar PV project, and (4) the concept of sustainability assessment for site selection was considered by estimating a composite score that groups each alternative considering three possible categories of sustainability: Highly sustainable, Sustainable, and Unsustainable.

Based on these contributions, this doctorate proposes a set of insights for policymaking focused on mainstreaming and scaling up sustainable renewable energy-based systems in non-electrified areas of developing countries. This thesis may offer some direction for project developers and potential investors willing to undertake sustainability assessments in the rural electrification sector.

Keywords: rural electrification; electricity access; energy policy; off-grid energy planning; off-grid energy systems, sustainability assessment; sustainable development.

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To Emma and Cristina.

List of acronyms and abbreviations

Acronym	Definition
BNA	Basic Needs Approach
BESS	Battery Energy Storage Systems
CAPEX	Capital Expenditure
CEPAL	Nations Economic Commission for Latin America and the Caribbean
CO_2	Carbon Dioxide
CFL	Compact fluorescent lamps
CNM	National Centre of Monitoring for the ZNI
CREG	Regulatory Commission for Energy and Gas
DFI	Development finance institutions
FAER	Fund for the electrification of interconnected rural areas
FAER	Fund for the electrification of interconnected rural areas
FAZNI	Financial support fund for the electrification of non-interconnected areas
FENOGE	Non-conventional energy resources and Energy Efficiency Fund
FNCER	Non-conventional energy resources
FNR	National Royalties Fund
FTSP	Fund for the development of the Plan "We are all Pazcifico"
GDI	Gender Development Index
GHG	Greenhouse Gas
GII	Gender Development Index
GIS	Geographic Information System
HDI	Human Development Index
IDB	Inter-American Development Bank
IEA	International Energy Agency
IHDI	Inequality-adjusted Human Development Index
IPSE	Institute for the Planning and Promotion of Energy Solutions in the non-interconnected zones
KfW	Kreditanstalt für Wiederaufbau (German Credit Agency for Reconstruction)
LAC	Latin America and the Caribbean
LCOE	Levelised cost of electricity
LED	Light Emitting Diode
LV	Low Voltage
MME	Colombian Ministry of Energy and Mines
MV	Medium Voltage
MMR	Mixed Methods Research

MPI	Multidimensional Poverty Index
MTF	Multitier Framework
NDF	Nordic Development Fund
NGO	Non-governmental organization
NCER	Non-Conventional Energy Resources
OLADE	Latin American Energy Organization
OPEX	Operational Expenditure
PAYG	Pay As You Go
PERS	Sustainable Rural Energization Plans
PEVD	Programa de Electricidad para Vivir con Dignidad
PL	Poverty Line
PNER	National Plan for Rural Electrification – Colombia
PV	Photovoltaic
RE	Renewable Energy
SHS	Solar Home Systems
SDG	Sustainable Development Goal
SIN	National Interconnected System
SSPD	Superintendency of domiciliary public services
UN	United Nations
UNDP	United Nations Development Program
UPME	Planning Unit on Mining and Energy
VMEEA	Vice Ministry of Electricity and alternative energy
WB	World Bank
ZNI	Non-interconnected zones

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1. ntroduction

Scaling up sustainable renewable energy (RE) solutions such as stand-alone systems and minigrids is a key condition to achieve universal access. Yet, there are still multiple challenges hindering this process. Policy measures and effective interaction between stakeholders are required to support rural electrification initiatives. Within this context, sustainable rural electrification plans that account for key dimensions that guarantee the long-term sustainability of off-grid projects could contribute to this purpose. This thesis is framed within the context of sustainable energy planning in remote rural areas and discussion around long-term sustainability, decentralised technology options, drivers of risk, and the role of key stakeholders in scaling up sustainable off-grid rural electrification. This introduction presents the research context, research framework, main objectives, research questions, and the structure of this thesis.

Providing reliable electricity access to remote and rural communities is a necessary condition for fostering social and economic development. Some of the positive benefits of accounting for energy services include: reducing poverty, improving access to health services, education, and information, promoting female empowerment, and economic growth, among others. (IEA et al., 2021; Kempener et al., 2015; Meuser et al., 2017; Williams et al., 2015).

Unfortunately, nearly 759 million people across the globe still lack this basic service (as of 2019) and about 53% of them live in Sub-Saharan Africa (IEA et al., 2021) (See Figure 1.1).

Table 1.1 shows a comparative review of the three countries with the lowest energy access in South Asia, Sub-Saharan Africa, and South America (as of 2019). Although progress in rural electrification has been improving, disparities between rural and urban electrification continue to prevail. Urban areas have been approaching universal access, with an electrification rate of about 97%, but in contrast, in rural areas, the electricity access rate is about 84% (640 million unserved people) (IEA et al., 2021).

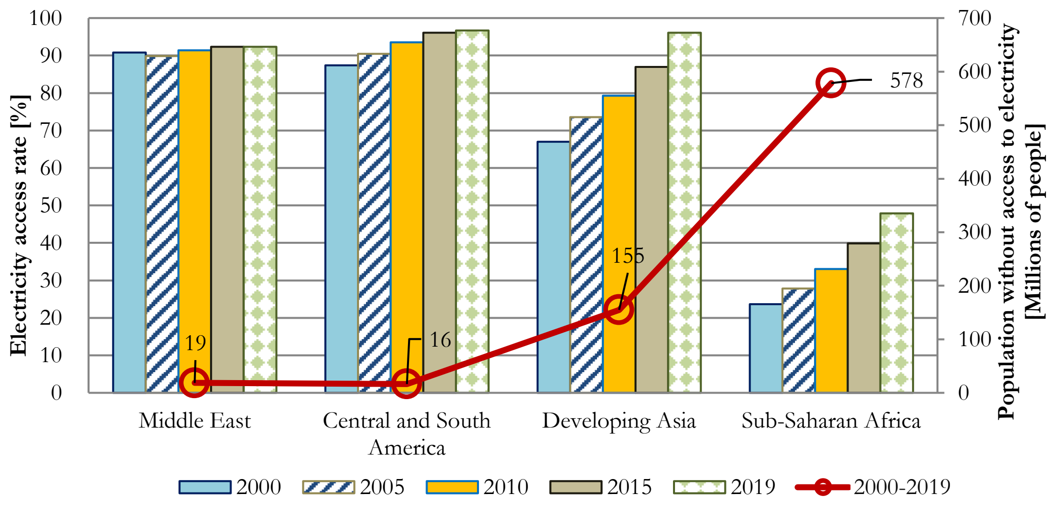

Figure 1.1 Population without access to electricity as of 2019. Source: (IEA, 2020)

At the country level, the Democratic Republic of the Congo alone has the world's largest electricity access deficit (about 79 million) followed by Nigeria (77 million), and Ethiopia (60 million) (IEA, 2020). In other regions, such as South America, the three worst scenarios are Bolivia, Peru, and Colombia, where rural electricity access rates are below 90% (as of 2019) (World Bank, 2019).

Table 1.1 Comparison of estimated electricity access rates and other socioeconomic indicators between three regions (as of 2019). Source: Adapted from (World Bank, 2019).

Region	**Country**	**Population [Million]**	**% of Rural Population**	**Electrification rates**			**People without electricity in rural areas [Million]**	**Per capita energy consumption (kWh/capita)**	**HDI (2019)**
				Total	**Urb**	**Rur**			
South Asia	Pakistan	185.5	64.2	93%	>99%	79%	<1	471.0	0.54
	Bangladesh	159.4	66.5	97%	>99%	86%	1,6	310.4	0.57
	Myanmar	53.0	69.1	68%	92.5%	69%	<1	471.0	0.58
Sub-Saharan Africa	Dem. Rep. of the Congo	73.7	57.8	9%	19%	<1%	79	69.7	0.44
	Nigeria	176.5	53	62%	91%	30%	77	144.5	0.51
	Ethiopia	97.4	81	47%	96%	34%	60	108.6	0.43
South America	Bolivia	10.6	32	93%	>99%	79%	<1	752.7	0.66
	Peru	31.0	22.8	97%	>99%	86%	1,6	1,307.5	0.73
	Colombia	47.8	20.6	97%	>99%	86%	<1	1,289.6	0.72

In the selected countries of South Asia and Sub-Saharan Africa, more than 50% of the population lives in rural areas, which accounts for about 169 million people without access to electricity. Overall, among the nine countries, the Democratic Republic of the Congo has the highest deficit of electricity access in rural areas: 57.8 % of the population lives in rural areas and roughly 1% of them have access to electricity. In addition, levels of electricity consumption vary across countries. While a person in Peru consumes about 1,307.5 kWh of electricity per year, a person in Ethiopia consumes twenty times less or 69.6 kWh. Although this value exceeds the minimum level of electricity consumption that a person in rural areas needs to gain 'modern energy access' (i.e. 50 kWh in rural areas vs 100 kWh in urban areas per year (Moss et al., 2020)), it is only enough to power a lightbulb and charge a mobile phone, reflecting that energy access alone does not imply accounting for sufficient energy supply to enable productive uses of energy.

Table 1.1 also shows values for the Human Development Index (HDI), which allows making a comparison among countries, measuring three dimensions of human development over time: life expectancy, adult literacy, and enrolment at the primary, secondary, and tertiary levels, and income (UNDP, 2020). As a result, countries can be grouped into four categories: a country with a HDI of 0.8 or greater is considered very highly developed, a country with a HDI value between 0.7 and 0.799 is recognized as highly developed, a country with a HDI value between 0.55 and 0.699 is included in the medium development category and those with HDI lower than 0.55 are classified as countries with a low human development (UNDP, 2018). According to Gómez et al. (2010), the HDI has served as an *"evaluation tool for measuring the impact of electrification in welfare improvement"* (p. 6259), since large increases in energy use are associated with high values for the HDI (UNDP, 2016). In this case, Ethiopia and the Democratic Republic of the Congo account for a low HDI and the lowest energy consumption rates. The rest of the listed countries have a medium HDI, e.g. Bolivia, or a high HDI, e.g. Colombia and Peru.

Within this context, rural electrification (RE), the process of delivering electricity to rural and remote areas, has become a priority on the agenda of developing countries (IRENA, 2020a). Governments across the world have identified the need of achieving universal electricity access by adopting the United Nations Sustainable Development Goal (SDG) 7, which aims to *"ensure access to affordable, reliable, sustainable, and modern energy for all by 2030"* (IEA et al., 2021, p. 108). However, coverage levels continue to be low despite many decades of electrification efforts (Banal-estañol et al., 2017a) and according to the 2021 Energy Progress Report tracking SDG 7, the world is falling behind to reach this goal and about 660 million people will still lack access to electricity by 2030 (IEA et al., 2021). In addition, the COVID-19 pandemic has threatened electrification progress by increasing investors' risk perception and shifting public funding priorities in developing countries (IEA et al., 2021).

Based on the World Bank's "State of Electricity Access Report 2017", it is expected that to advance toward universal access, countries need to *"expand access more rapidly than demographic growth"* (World Bank, 2017a, p. 23). Sub-Saharan Africa is falling behind to reach this goal by 2030 since access to electricity is growing at 5.4 % annually, against the needed 8.4 %. Meanwhile, Latin America, East Asia, and South Asia will be able to reach universal access by 2030, *"assuming conditions of constant growth in electricity, constant growth in population, and no major changes in political willingness and financial investments in increasing access"* (World Bank, 2017a, p. 16).

This thesis focuses on the particular case of South America, where roughly 6 million people still live without electricity access (as of 2019) and most of them live in remote rural areas (ARIAE et al., 2021). During the last decades, South America has gone through reforms in the energy sector, that together with the countries' democratization and economic growth, have attracted significant investments in rural electrification projects. Based on the Global Tracking Framework (GTF), a World Bank's set of metrics that measures progress in energy access over time, rural electrification rates in South America increased from 72.8% in 2000 to about 92% in 2019 (World Bank, 2019). The greatest cases correspond to Bolivia and Peru, where coverage increased by about 60% between 2000 and 2019. In contrast, in Colombia, rural electrification increased by less than 1%, between 2010 and 2019. Some explanations for this situation could relate to: (i) an increase of population growth in rural areas without access to electricity; (ii) priority investments given to urban electrification; and (iii) difficulties in implementing RE projects due to the country's armed internal conflict, mainly affecting the rural areas of the country.

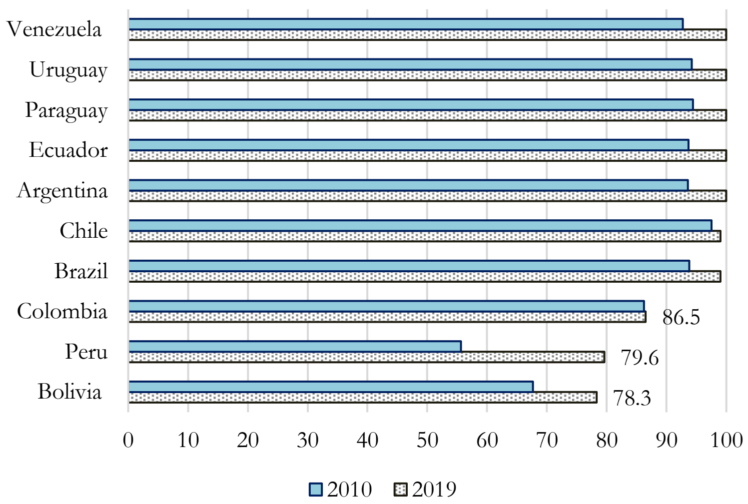

Figure 1.2 Rural electrification rates in South America, 2000–2019 (%). Source: (World Bank, 2019).

However, as of 2019, Bolivia is still the country with the lowest rate of rural electrification in South America, followed by Peru, and Colombia (See Figure 1.2)

1.1. Research Framework and Structure

This doctoral thesis is concerned with scaling up sustainable rural electrification planning in developing countries. Addressing the energy access gap and progressing toward achieving SDG7 requires a collaborative effort between governments, energy utilities, private-sector companies, funding agencies, and national and international developmental organizations. However, there are still key challenges hindering the process of providing electricity access in a technically, environmentally, and economically efficient manner, in remote off-grid areas of the world. To summarise, some of these challenges are: (i) lack of a prioritisation guideline to effectively allocate public funds in rural electrification interventions; (ii) lack of a sustainable and integrated rural electrification planning that integrates different electrification modes; (iii) lack of a well-defined regulatory framework for rural electrification; (iv) lack of incentives, sustainable tariffs and business models to promote private sector participation, (v) lack of coordination between public institutions in charge of the country's rural electrification policy, (vi) lack of technical expertise of off-grid energy service providers, (vii) high Operations and Maintenance (O&M) of the projects, (viii) low payment capacity of the communities, (ix) local geographic constraints of projects, (x) lack of communities' awareness and appropriateness of the projects, among others (Ahlborg, 2012; Akinyele et al., 2018; Bhattacharyya and Palit, 2016; DNP, 1999; Hoeck et al., 2021; IDB, 2016; Palit and Bandyopadhyay, 2017; Williams et al., 2015). These challenges are not particular for each case study analysed in this thesis, but they pose importance to other developing countries with similar geography, climate, development conditions, and facing energy access deficits.

To better understand the knowledge gap filled by this thesis, it is worth elaborating upon some of the aforementioned issues:

- **The need to rely on complementary socioeconomic indicators when prioritising rural electrification interventions to capture other variables linked to socioeconomic development.**

The objectives of rural electrification programs are not only to provide people with electricity access but also to promote rural development and tackle poverty reduction in rural areas. One way to achieve this purpose is to give priority to the poorest when selecting areas for electrification programs. This process requires relying on different poverty and development measures, including the basic needs approach (BNA), the income poverty measure or the poverty line (PL) approach, and the capability approach (including the family of human development indices (HDI), the Inequality-adjusted Human Development Index (IHDI), the Gender Development Index (GDI), the Gender Inequality Index (GII), and the Multidimensional Poverty Index (MPI) (Parra-peña et al., 2013; Santos et al., 2010).

This thesis provides an in-depth analysis of the suitability of using the Unsatisfied Basic Needs Index as the social criterion to select the areas that should be prioritised for rural electrification projects, within a prioritisation process or methodology that might also consider other factors, such as density, distance from the grid, topographic constraints, among others.

. In this respect, using complementary socio-economic indicators, such as the Multidimensional poverty index (MPI) could complement the traditional UBN index by capturing more relevant information that could lead to a more accurate poverty measurement and rural electrification interventions.

- **Lack of a sustainable and integrated rural electrification planning**

As authors in Rahman et al. (2013) argue, *"a large number of off-grid rural electrification projects have failed because the focus was given on technical installation without paying sufficient attention to the long-term sustainability"* (p. 589). Also, as highlighted in Akinyele et al. (2018) and World Bank (2008), maximising the chances of sustaining the operation of an off-grid electrification project over the long- term depends on the interaction of key elements, namely the social, technical, economic, and policy/institutional perspectives affecting the development and widespread of off-grid energy solutions.

Within the context of distributed off-grid energy generation, several definitions have been provided for sustainability (Hazelton et al., 2015). Traditionally, the concept of sustainability is associated with the triple bottom line (TBL) framework, composed of three key dimensions of sustainability: social, environmental, and economic principles (Boliko and Ialnazov, 2019; Marques et al., 2015). However, as presented in Cherni et al. (2007), Fetanat and Khorasaninejad (2015), Fuso Nerini et al. (2014), Ghasempour et al. (2019), Haddad et al. (2017), Hinestroza et al. (2021), Latinopoulos and Kechagia (2015), Pérez-Gelves and Díaz-Florez (2020), Rahman et al. (2013), Sánchez-Lozano et al. (2013), and Vafaeipour et al. (2014), Zhang et al. (2019), the TBL approach is not sufficient to capture all the perspectives that affect the sustainability of rural electrification projects. A sustainability assessment requires accounting for a set of criteria that are related to the SDGs and cover multiple dimensions of sustainability (Marques et al., 2015).

In this thesis, rural electrification projects' sustainability is considered as the *"perceived potential for a system or project to endure, build a self-perpetuating capacity within a community, and ultimately reach the end of its pre-determined lifespan or evolve into another beneficial form"* (Louie et al., 2014, p.71). The model proposed herein accounts not only for technical constraints, and economic-financial feasibility but also for socio-cultural dynamics and environmental consequences of rural electrification projects, as presented in Figure 1.3. Thus, the scope of the sustainability principles is expanded to also integrate a multidimensional perspective for achieving sustainable energy planning in off-grid rural communities. In doing so, a multi-criteria decision-making (MCDM) approach was implemented to assess the suitability of potential sites to implement off-grid solar PV projects in South America.

The thesis thus also facilitates an in-depth discussion on how addressing the main issues or challenges in the rural electrification sector requires these five elements of sustainability. This is, *"all the dimensions need to work together to overcome the barrier and achieve the desired sustainable energy development, which is beyond the traditional techno-economic planning perspective"* (Akinyele et al., 2018, p.4).

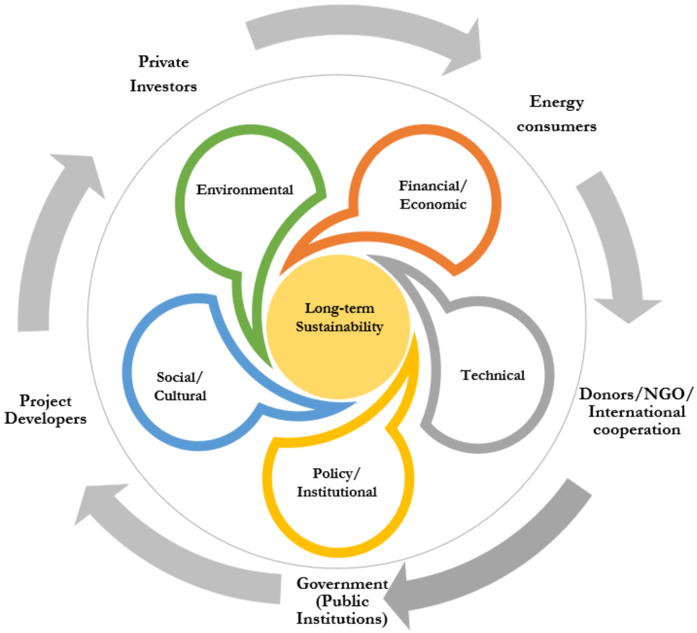

Figure 1.3 Dimensions to assess the sustainability of off-grid projects. Source: Adapted from (Akinyele et al., 2018; López-González et al., 2019; Rahman et al., 2013)

- **The need to scale up decentralised off-grid solutions**

When extending the national transmission system is not a techno-economic feasible option, especially due to the geographic conditions of the country, there are other alternatives to reach the most remote rural communities. Historically, the most common approach to rural electrification across the world has been grid extension (Barnes, 2007, Niez, 2010). Within this option, new connections derive from extending the existing grid or the grid densification. The first case implies extending the existing medium voltage (MV) and low voltage (LV) distribution grid to connect households or other customers to the central energy supply system (i.e. the national power generation, transmission, and distribution system) (Moner-Girona et al., 2018). Grid densification divides into two categories: (1) grid densification by installing additional transformers and (2) densification through an existing low-voltage distribution grid, by connecting additional households (EIA, 2020). Overall, different countries have adopted different policies to promote this alternative. In Bolivia, for instance, according to the 2025 National Plan for the Bolivian electricity sector, 70% of the rural electrification projects aimed at achieving universal access by 2025, will depend on extending the grid (Hinestroza-Olascuaga et al., 2021).

This thesis focuses on exploring the convenience of installing minigrids (MG) and stand-alone photovoltaic (PV) systems, by implementing a techno-economic evaluation of these off-grid technologies compared to diesel-powered generation, based on the Levelised Cost of Electricity (LCOE). These off-grid solutions provide several technical advantages, including reduced transmission losses, limited upfront capital expenditure, and the ability to accommodate on-site, renewable generation. As presented in Chapter 8 and Chapter 9, scaling up the use of these off-grid solutions require regulations reforms, sustainable business models, and accounting for certain uncertainties and potential risks that could affect the participation of the private sector in rural electrification projects. However, there are still key concerns related to these systems, including

- **The need to unlock private investments in the off-grid electrification sector**

One of the key factors towards achieving universal access is enabling private investments in the rural electrification sector, as public resources are scarce. Historically, a large part of the investments undertaken to expand the electricity service has been public and the pace of progress in achieving universal access has often, to date, been slow (IEA, 2017). Off-grid electrification projects are often considered high-risk investments by utilities and off-grid service providers, mainly due to the uncertainty around revenues, project sustainability, and potentially low returns. In consequence, enabling private sector investments in off-grid electrification represents a feasible alternative to speed up electricity access in different developing countries.

In the literature, many authors (Bekker, 2010; Gujba et al., 2012; Hazelton et al., 2015; IDB, 2015; Khodayar, 2017; Schmidt et al., 2018, 2013; Wagemann and Manetsgruber, 2016; Williams et al., 2018) have provided a relevant and worthwhile background in identifying the main uncertainties and resulting risks of RE off-grid projects, with contributions in different directions. However, while many authors have qualitatively assessed risks faced by investors in off-grid projects, there has been little work to quantify these risks and propose policy instruments to mitigate them. This thesis addresses this gap by implementing a qualitative and quantitative approach that assists investors in making more informed investment decisions. In doing so, it implements a stochastic discount cash flow technique- the net present value (NPV) with Monte Carlo simulation- to incorporate the main uncertainties and quantify the business and investment risks of off-grid solar PV projects. In addition, this thesis provides some policy measures that could support the government's effort in unlocking private investment in off-grid areas, namely, key strategies that mitigate the risks that specific uncertainties may influence.

1.2. Principal and Specific Objectives

The broad objective of this thesis is to:

- Demonstrate the validity and limitations of different methods to support rural electrification planning in developing countries.

The Specific Objectives are:

- Identify how universal electricity access has been pursued in different countries of South America and what achievements have been reached to critically assess the suitability of current prioritisation approaches in rural electrification interventions.
- Evaluate to what extent a multidimensional approach can capture all the perspectives that affect the long-term sustainability of rural electrification projects.
- Identify critical uncertainties and potential derived risks affecting the private sector participation in the rural electrification sector and propose policy measures that promote a coordinated interaction between key stakeholders.

1.3. Research Questions

The previous sections demonstrate the importance of closing the energy access gap by tackling key challenges affecting the implementation of new electrification projects and by defining public policy measures that support energy access interventions. Based on this need, in this thesis, I address the following research questions which are linked to the specific objectives of this research (See Figure 1.4):

1. Are current electrification programs reaching the poorest rural households? *(The case of* **Bolivia***)*
2. Which factors determine the long-term sustainability of off-grid electrification projects in rural and remote communities? *(The case of* **Bolivia, Peru, and Colombia***)*
3. Which are the key challenges and main drivers of risk in off-grid electrification projects? *(The case of* **Colombia***)*
4. To what extent are current rural electrification policy measures and interventions supportive of promoting a sustainable rural electrification planning? *(The case of* **Colombia***)*

1.4. Ph.D. thesis structure

Figure 1.4 depicts the research framing, the structure of the thesis, and the relations between the chapters. Overall, this research is divided into ten chapters. Six of them focused on answering one to two research questions. On the right, Figure 1.4 presents the sustainability dimensions that contribute to an integrated sustainable rural electrification planning and their link to each research question addressed in this thesis.

1.5. Chapter Summaries

A brief summary of each chapter is presented next.

Chapter 1 to *Chapter 3* provide a general context of the background and research motivation of this thesis. It presents the research problem, research objectives, research strategy, methods, and structure of the thesis, including the research questions addressed in each chapter.

Chapter 4 presents a brief analysis of the rural electrification policy of developing countries, namely Bolivia and Peru. It provides an overview of the main lessons derived from rural electrification efforts and the role of public interventions in providing electricity access to last-mile rural communities.

Chapter 5 provides an overview of key hurdles or challenges hindering the progress toward providing electricity service to the last-mile communities of Colombia. Following discussions with multiple stakeholders and experts involved in the off-grid sector of Colombia, this chapter identifies a set of key challenges grouped into four dimensions, namely financial/economic, social/cultural, technical, and policy/regulatory.

Chapter 6 focuses on the social dimension of the sustainable planning framework proposed in this thesis. It provides an overview of the prioritisation methodologies implemented in Bolivia and Colombia to allocate public funds, namely, to implement rural electrification projects. Results indicate that using complementary socio-economic indicators, such as the MPI could complement the traditional UBN index by capturing more relevant information that could lead to more accurate poverty measurement and rural electrification interventions, not only in Bolivia but also in Colombia.

Chapter 7 identifies the key factors that determine the long-term sustainability of off-grid electrification projects in rural and remote communities considering the private sector's point of view, using a MCDM method with 13 criteria and 5 dimensions. It provides an overview of the main criteria influencing the decision-making of deciding where to invest in rural electrification projects concerning their attractiveness for off-grid electrification, specifically stand-alone systems, using the case study of Bolivia, Peru, and Colombia.

Chapter 8 focuses on the economic dimension of the sustainable planning framework proposed in this thesis. In this regard, it provides a brief analysis of the key uncertainties and perceived risks arising in the off-grid rural electrification sector, based on the literature review and the private sector's point of view, while using a stochastic discount cash flow technique to incorporate these uncertainties and quantify the business and investment risks associated with an off-grid solar PV project. The technique is applied to the case of Colombia, wherein major contributors to risk are the variability in revenues and the annual revenue growth rate.

Chapter 9 explores the role of decentralised energy solutions, namely microgrids in providing and/or improving the electricity service provision in remote rural areas. Using the case of Colombia, this chapter presents a techno-economic evaluation of different off-grid technologies vs the current diesel-powered plants, based on the LCOE. Additionally, this chapter examines the role of energy efficiency in expanding electricity access in rural areas, based on qualitative and quantitative research methods.

Chapter 10 summarizes the main conclusions drawn from the research questions posed for this study. This thesis concluded that Colombia's rural electrification efforts are not enough to achieve universal access by 2030. In this regard, a set of policy recommendations for tackling the identified challenges are proposed. Reaching the last-mile communities with long-term sustainable projects, not only requires an integrated energy planning but also, effective coordination between different stakeholders. In addition, potential future research topics are identified.

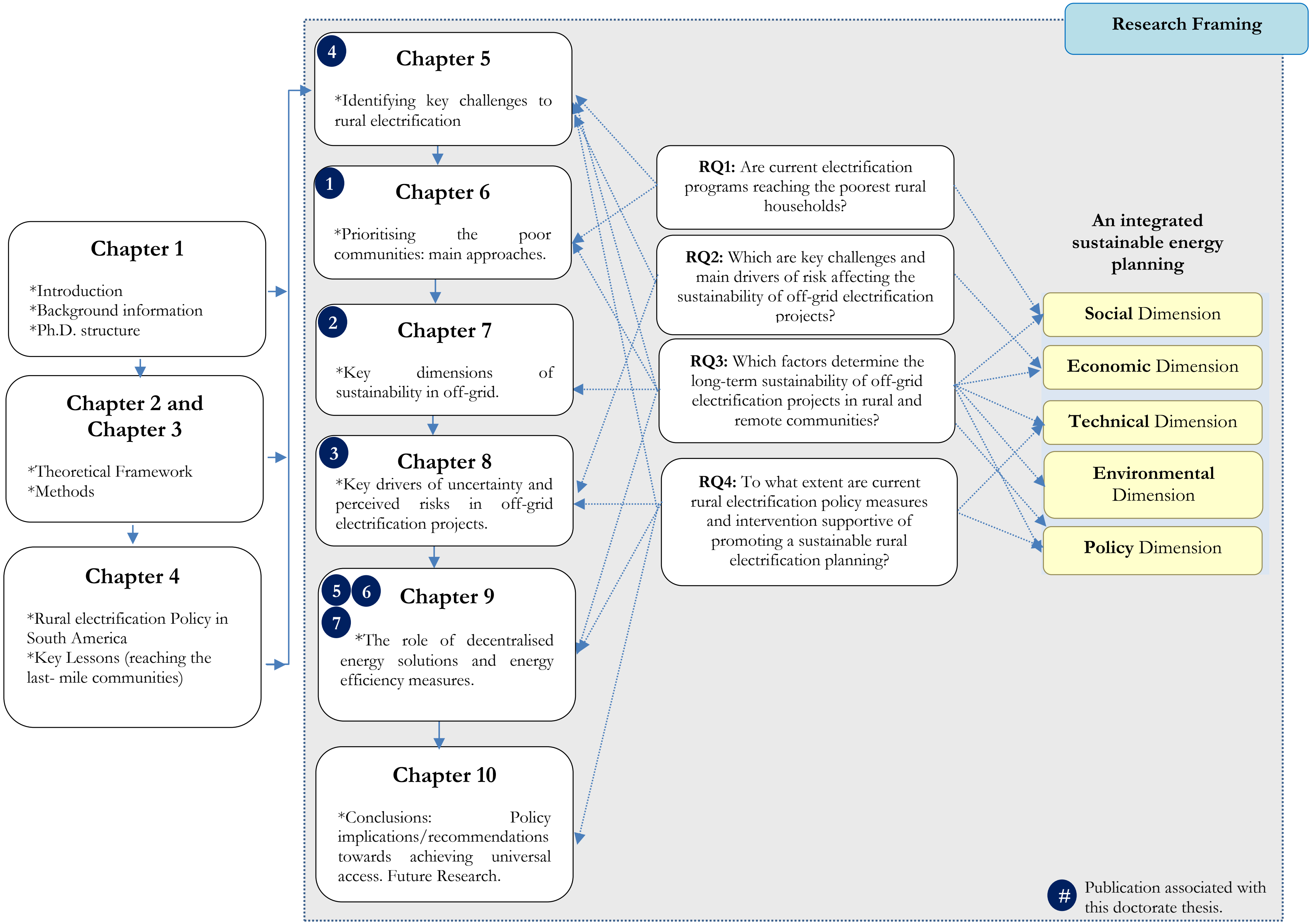

Figure 1.4 Research framing and structure of the thesis, including the research questions addressed in each chapter

1.6. List of publications

The thesis is composed of five scientific publications either published or submitted for evaluation. These papers comprise Chapters 4–9 and bring together the most significant aspects of the studies conducted between February 2016 and July 2021.

Journal papers:

I. Laura M. Hinestroza-Olascuaga, Pedro M.S. Carvalho, Célia M.S. Cardoso de Jesus, Electrification for the elite? Examining whether electrification programs reach the poor in Bolivia, *Energy Research & Social Science*, 71, 2021, 101813, ISSN 2214-6296, https://doi.org/10.1016/j.erss.2020.101813.

II. Laura M. Hinestroza-Olascuaga, Pedro M.S. Carvalho, Célia M.S. Cardoso de Jesus. Using a Multi-Criteria Model to Assess the Suitability of Potential Sites to Implement Off-Grid Solar PV Projects in South America. *Sustainability*, 2021, 13 (14), 7546. https://doi.org/10.3390/su13147546.

III. Laura M. Hinestroza-Olascuaga, Pedro M.S. Carvalho, Célia M.S. Cardoso de Jesus. Lowering risk intolerance to unlock private investments in renewable energy-based rural electrification. *Energy for Sustainable Development,* 2023, 74, ISSN 0973-0826 https://doi.org/10.1016/j.esd.2023.02.011.

IV. Laura M. Hinestroza-Olascuaga. Achieving Universal Access in the off-grid areas of Colombia: challenges and policy implications (forthcoming).

V. How rural electrification efforts can benefit from the implementation of minigrids systems? (forthcoming).

Conference papers:

VI. Laura M. Hinestroza-Olascuaga and Célia M.S. Cardoso de Jesus (2017). Micrograds as an alternative energy solution for off-grid rural areas in Colombia. *23rd Annual International Sustainable Development Research Society (ISDRS) Conference*. Bogota, Colombia. June 14th-16th, 2017, pp. 153, ISBN: 978-958-774-607-5.

VII. Laura M. Hinestroza-Olascuaga, Pedro M.S. Carvalho, Célia M.S. Cardoso de Jesus Efficiency for access: the role of high performing appliances as a potent catalyst of scaling energy access in off-grid areas. 2022 IEEE International Conference on Environment and Electrical Engineering and 2022 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Prague, Czech Republic, 2022, pp. 1-6, https://doi.org/10.1109/EEEIC/ICPSEurope54979.2022.9854759.

I, Laura Marcela Hinestroza Olascuaga, confirm my contribution to the above papers were the design, development, and finalisation of all drafts. As the lead author for all of them, I was responsible for selecting and coordinating the contributions of the other co-authors. I selected the journals, and I am ultimately responsible for all the content included within these scholarly publications and in the present document. At the end of each published paper, there is a more detailed breakdown of the roles and responsibilities of all the co-authors who helped to make these papers possible.

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2.Theoretical framework

This chapter presents the relevant literature and the theoretical framework associated with this research. A conceptual background on the concept of Sustainability is presented to understand the need of integrating multiple dimensions within the rural electrification decision-making process and planning. Also, I provide background information on the relevant literature and existing methods that back up the focus of this thesis.

2.1. Electricity access and technology approaches

The term *'electricity access'* has received different definitions beyond binary metrics that measure access in terms of whether a household has or not an electricity connection. According to the U.S. Energy Information Administration (EIA), electricity access is *"the ability to acquire electricity, whether on-grid or off-grid, whether provided by a central utility, a private company, or the users themselves, and whether generated from large, central power stations, local minigrids, or small stand-alone generators, and regardless of the source of power"* (EIA, 2020, p.6). In 2015, the World Bank Group proposed a quantitative definition where electricity access is quantitatively measured within multi-tier standards or progressive tiers of access, from Tier 1 to Tier 5 (See Table 2.1), where the level of demand for a household begins with small appliances and expand to more electricity-intense uses (The World Bank Group, 2015). Also, Table 2.1 presents different tiers of consumption which depend on the hours of use for electric appliances and vary from tiers of energy supply.

Table 2.1 Multi-tier approach to measuring access to electric services (residential). Source: (EIA, 2020; WB, 2015)

Tier	Electricity Supply*	Examples	Annual Electricity Consumption (kWh)
Tier 0	Disconnected	-	<4.5
Tier 1	Very low power (Min. 3 W) HPD: Min. 4Hr	Task lighting and phone charging or radio	≥ 4.5
Tier 2	Low power (Min. 50 W) HPD: Min. 4Hr	General lighting, a television, or a fan	≥ 73
Tier 3	Medium power (Min. 200 W) HPD: Min. 8Hr	Tier 2 plus any medium power appliances, e.g., a printer, refrigerator, freezer, or washer	≥ 365
Tier 4	High power (Min. 800 W) HPD: Min. 16Hr	Tier 3 plus any high-power appliances, e.g., an iron, hair dryer, toaster, or microwave	≥ 1,250
Tier 5	Very high power (Min. 2 kW) HPD: Min. 23Hr	Tier 4 plus any very-high-power appliances, e.g., an air conditioner, water heater, or electric cooking	≥ 3,000

*Indicative Power capacity; HPD stands for "Hours per day"

Electricity access is essential but not sufficient to move customers from simple lighting systems (Tier 1) to full-featured energy solutions that can provide a range of useful services such as refrigeration, cooling, and communications (Tier 4 to 5). There are some supply-side and demand-side constraints affecting the off-grid appliances market. On the supply side, remote communities often have no choice other than available solutions for lighting and other basic energy services offered by the local service provider. On the demand side, affordability to pay the electricity and appliances price, is a major consideration, given the limited purchasing power of rural households and the variability in their income streams (World Bank, 2017b).

Within this context, with more efficient appliances, the off-grid energy industry could move beyond lighting, enabling the widespread of these technology options and thus, improving the lives and incomes of under-served rural communities. Also, the off-grid sector has the potential to drive climate resiliency and enable a billion people to switch to clean energy technologies (GOGLA, 2020).

In the literature, several studies present methods to estimate demand in areas that have never had electricity, including bottom-up methods based on assumed appliance use or simple averages of consumption from systems installed in other communities (Mandelli et al., 2016; Williams, 2017). For instance, Ye et al. (Ye et al., 2018) assessed the determinants of residential energy demand in South Africa, combining data from South African government surveys such as electricity rates from the regulator, and household expenditures. They found that household income and the price of electricity were the main determinants of electricity demand. Al-Bajjali & Shamayleh in 2018 (Al-Bajjali and Shamayleh, 2018) analysed the determinants of electricity consumption in Jordan between 1986 and 2015, using six independent variables: Gross Domestic Product (GDP), electricity prices, population, urbanisation, the structure of the economy, and aggregate water consumption. Based on a multivariate data model, they found that GDP, urbanization, the structure of the economy, and total water consumption, are positive and statistically significant related to electricity consumption, while electricity prices were negative and statistically significant related to electricity consumption. Sakah, et al. (2019) (Sakah et al., 2019), evaluated the influence of different socio-economic factors on household electricity demand. Using data from residential electricity consumption surveys and multiple linear regression analysis, they identified the statistically significant indicators of appliance ownership and household electricity consumption in Tema, Ghana. As a result, they found that the ownership of air conditioning, freezer, fan, refrigerator and television; and changes in construction and socioeconomic factors, such as energy efficiency awareness and practice, income, the size and surface of the home, show a high statistical significance and, together, explain the variation of 57% in the total electricity consumption of the homes.

Following the existing literature, this thesis analyses the case of Colombia, where there is little empirical evidence devoted to studying the key drivers of electricity consumption in off-grid rural and remote areas (IPSE, 2020a; UPME, 2016a). Thus, it not only provides an in-depth understanding of consumer demand and preferences for off-grid appliances, but it also presents estimates of electricity-consuming appliance ownership, which could contribute to improving the design process of off-grid energy systems to be installed and their bankability.

Based on this Multi-Tier approach, there are mainly three technology options for expanding electricity access, with example implementations in the developing world: (1) Grid extension, (2) Dispersed centralised systems or standalone systems (SAS) powered either by renewable energy sources or by diesel generators and (3) Compact centralised systems or micro/minigrids (MG) (Rojas-Zerpa and Yusta, 2015). When extending the grid is economically unviable, decentralised solutions represent the least-cost way to provide electricity service (IEA et al., 2021). According to the International Energy Agency (IEA), nearly 60% of additional generation needed to achieve universal access by 2030 will come from these off-grid systems, which can be either minigrids or stand-alone systems (IEA, 2011; Lucas et al., 2020).

The size of these systems ranges from home installations to relatively large minigrids that provide 24 hours of electricity a day to a large community, including for productive uses (Slough et al., 2015). The major advantage of this distributed energy generation is that such technology options can be installed far from the national grid, reaching the last-mile communities, while avoiding the cost of extending the grid over long distances (Brass et al., 2012, Urpelainen, 2014).

Table 2.2 Comparative review between different electrification alternatives. Adapted from (World Bank, 2017a; Wyman, 2017)

Features	**Public Grid Extension**	**Off-grid energy systems (Decentralised)**	
Type of system	**Centralised**	**Minigrids**	**Stand-alone systems**
Definition	Extension of the medium voltage (MV) and low voltage (LV) distribution grid to connect households or other customers to the national electricity grid. Two approaches: grid extension and grid densification.	Small-scale power stations where electricity is distributed to a limited number of customers, which can be off-grid or interconnected to the central grid.	Isolated power system powered either by RE sources or by diesel generators, which usually supplies one or a limited number of rural customer (s) without a distribution grid
Scale	National, regional, and international	Community/ Villages	Household-level
Type of energy resource	Fossil fuel-based systems, hydropower plants, Wind and solar generation power plants	Micro-wind systems, micro-hydro systems, biomass, or local solar power plants with battery energy storage systems (BESS)	Diesel generation, Solar Home Systems (SHS), DC Solar Kits
Typical features	*Urban and peri-urban areas in developing countries (i.e. households living close to the local utility grid but which are not yet connected). *AC, Large scale	*Typically deployed in rural areas with a higher population density. *Usually, AC compatible	*Rural areas *Often DC (not grid compatible)
Target customer (Load)	Residential, industrial, and commercial	Residential and commercial	Residential
Number of customers	Thousands to millions	Dozen to hundreds	Usually, a dozen or less
Service Level- Multi-Tier Framework (MTF)	Tier 4-5	Tier 2-5	Tier 1-3
Typical size (installed capacity)	>~ 1 MW	1 kW to 10 MW	< 1 kW
Business model (revenue)	Fixed energy tariffs	Flexible tariffs & microcredit	Pay-as-you-go (PAYG) systems
Metering systems	Locally installed energy meters	Metering with mobile pre-payment system	Mobile phone charging services

Selecting the appropriate option between different off-grid technologies represents a critical decision for investors and project planners. Figure 2.1 summarises a typical decision-making process for selecting a particular electricity supply technology option.

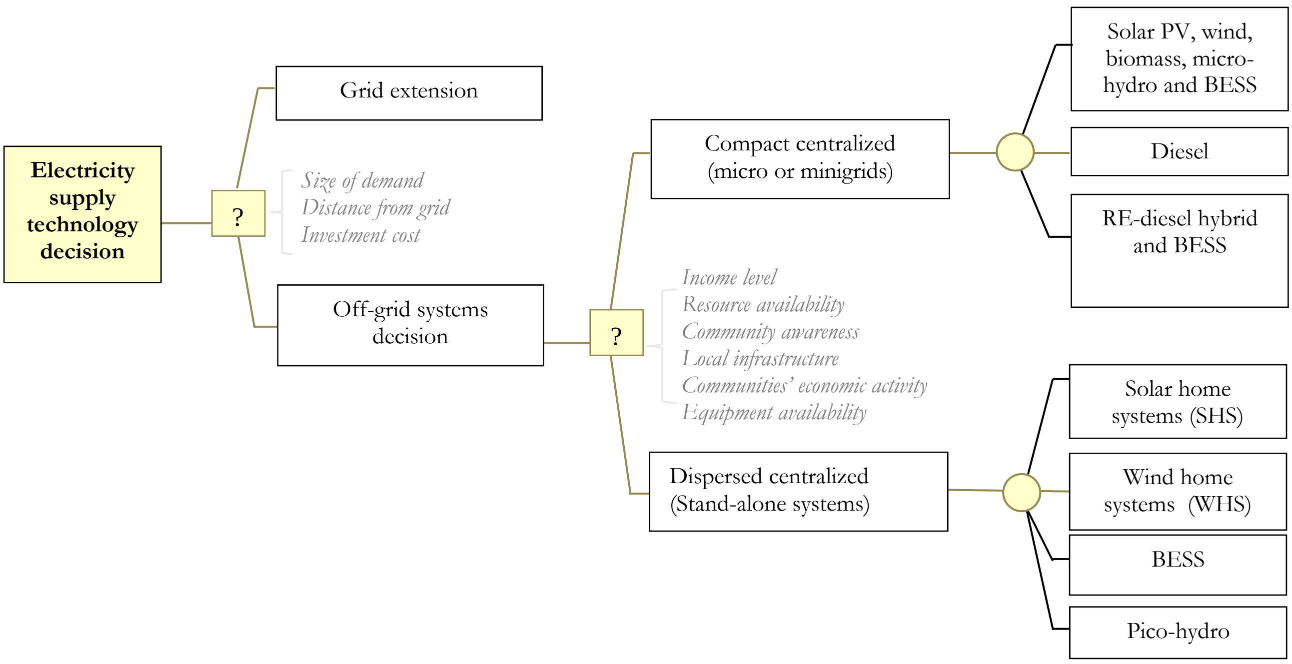

Figure 2.1 Decision-making process in off-grid project design and the typical technology choices. Source: Adopted from (Rahman et al., 2013; World Bank, 2008).

This decision-making process depends on accounting for different technical, social, economic, cultural, and environmental factors, including local geographic factors (i.e. topography, availability of local renewable energy resources, etc.), electricity demand, the ability to pay for electricity services, and cost trade-offs (i.e. initial capital cost and O&M costs) (EIA, 2020; Fabini et al., 2014).

This doctorate thesis not only evaluates the techno-economic feasibility of implementing hybrid minigrids compared to existing diesel-powered plants, which is typically the type of solution implemented in off-grid areas (e.g. Colombia), but it also investigates to what extent different local climatic conditions, the availability of renewable resources, the current community's consumption profile, among other aspects, affect the suitability of these systems.

2.2. Rural electrification: key challenges and drivers of risk

As presented in Chapter 1, governments across the world are increasing efforts to achieve universal access by 2030. However, there are still key challenges to overcome. These factors are well documented in the literature (Ahlborg, 2012; Akinyele et al., 2018; Bhattacharyya and Palit, 2016; DNP, 1999; Hoeck et al., 2021; IDB, 2016; Palit and Bandyopadhyay, 2017; Williams et al., 2015) and include analysis from different case studies in developing countries.

Palit and Bandyopadhyay (2017) highlight key historical challenges technical, financial, regulatory, and institutional that have hindered universal access to electricity in India. They summarise these issues in five aspects: subsidy trap and financial unavailability, improving household electricity level and supply reliability, absence of complementary schemes at the state level, absence of synergy with rural development efforts, and institutional and governance barriers. In Hoeck et al. (2021), the authors provide an overview of identified off-grid electrification challenges regarding policies, licensing, tariff setting, and financial, social, and technical aspects for the two selected off-grid sites in Namibia. Major challenges were found to be the involvement of communities in the design phase of a minigrid, the lack of standards and regulations issued by the government, main-grid arrival policy, tariff methodologies, and missing education among the off-grid communities. Palit and Chaurey (2011) present some specific challenges affecting rural electrification growth, including the following technical, financial, institutional, and governance barriers: projects failing to attain long-term sustainability, low concentration of electricity demand, low load factors that result in high O&M costs, low payment capacity, the high transaction cost of the projects, absence of standardized specifications of the systems, among others. Bhattacharyya and Palit (2016) describe some challenges affecting the minigrid-based business in developing countries, including a risky business environment, weak institutional arrangements, namely non-supportive regulatory and policy frameworks, "limited access to low-cost finance, and inadequacies in local skills and capacities". Ahlborg (2012) summarises the main drivers and barriers to rural electrification in Tanzania as a result of different discussions with energy sector stakeholders interested in rural electrification. Participants identified the following barriers as the most important: low institutional quality, lack of human capital, tariff system, and connection fees, lack of local engagement/capacity, and low access to required materials.

In particular, the lack of clear public policies together with a high perceived risk, have been a deterrent to investors' participation in off-grid electrification projects, mainly due to the uncertainty around revenues, project sustainability, scarcity of capital, potentially low returns, and the lack of clear and effective public policies (Williams et al., 2015). Private investors are looking for investments that not only create value but also create it at a greater rate than other investments with similar risks (Crundwell, 2008). Thus, the attractiveness of an off-grid electrification project will be measured by its expected financial return and its associated risks. Unfortunately, the terms of risk and uncertainty are usually used interchangeably, but they encompass different concepts. According to McManus & Hastings (2005), uncertainties can be defined as "things that are not known or known only imprecisely. They may be characteristics of the universe (e.g. statistical processes) or characteristics of the design process (e.g. information not yet collected); in either case, they are factual" (p. 2). Also, authors refer to the concept of Risks as the consequences of the uncertainties to a program or system, and they are often quantified as the probability of an uncertain event* the severity of consequences.

In the literature, many authors have studied the main uncertainties and perceived risks by private investors in the off-grid electrification sector (Gujba et al., 2012; Hazelton et al., 2015; Wagemann and Manetsgruber, 2016). Khodayar (2017) identifies the major challenges affecting the expansion planning of off-grid microgrids, namely the uncertainty about the availability of local renewable energy resources, the fluctuation of the energy demand, the availability of a logistic infrastructure to provide the service, and the lack of a secure stream of revenue to fund operating and maintenance costs, repay project debt, and provide a return to equity investors. Williams et al. (2018) present a risk analysis of the key uncertain variables affecting microgrid investments, using the case study of Rwanda. They concluded that major contributors to risk are fuel price volatility, uncertain electricity demand, and foreign exchange risk for investments in hard currency. Bekker (2010) follows a literature review and identifies a set of uncertainties related to the implementation of a minigrid household electrification project in KwaZulu-Natal, South Africa. Some of these factors are mainly associated with the uncertainty about the policy change, the demand (i.e. for power lower than expected), the willingness to pay incorrectly assessed, lower than expected revenues, poor acceptance of technology, the Grid encroachment, the technical failure of components in the field, and the theft of components. In Schmidt et al. (2018), authors introduce a taxonomy of nine investment risks and set out matching policy and financial de-risking instruments to promote private investment in solar photovoltaic (PV)-battery minigrids in developing countries. The identified investment categories refer to energy market risk, social acceptance risk, labour risk, developer risk, end-user credit risk, financing risk, currency risk, and sovereign risk. Schmidt et al. (2013) use the case of Indonesia to identify the main type of risks perceived by investors in energy access projects. These are: the energy market risk, the institutional/ licensing risk, the technology risk, and the financial risk. In IDB (2015), authors identify environmental and social risks related to off-grid projects in Colombia, including aspects such as land-use change, occupational health and safety, and greenhouse gas (GHG) emission leakage.

This doctorate thesis elaborates on the current literature to combine a qualitative and quantitative approach. It not only identifies the main drivers of risk, namely the set of uncertainties, but it also quantifies the perceived risks that prevent private companies from investing in off-grid electrification projects, as revealed by the results of this thesis.

2.3. Sustainability assessment in the rural electrification sector

In the context of electricity access, *"sustainability is emerging as a critical matter for policymakers and development practitioners"* (Eras-Almeida et al., 2019, p. 6), particularly in how to manage rural electrification projects, both in the short- and long-term view.

Traditionally, the concept of sustainability is associated with the triple bottom line (TBL) framework, composed of three key dimensions of sustainability: social, environmental, and economic principles (Boliko and Ialnazov, 2019; Marques et al., 2015). However, as stated in this study and along with some other authors (Cherni et al., 2007; Fetanat and Khorasaninejad, 2015; Fuso Nerini et al., 2014; Ghasempour et al., 2019; Haddad et al., 2017; Latinopoulos and Kechagia, 2015; Pérez-Gelves and Díaz-Florez, 2020; Rahman et al., 2013; Sánchez-Lozano et al., 2013; Vafaeipour et al., 2014; Zhang et al., 2019), believe that the TBL is not sufficient to capture all the perspectives that affect the sustainability of rural electrification projects. Table 2.3 presents a brief review of these studies, including the type of MCDM method applied to the sustainability assessment.

Table 2.3 Type of sustainability assessment associated with different MCDM studies

Author	Type of sustainability assessment	Type of project	Type of MCDM method	Main criteria
Zhang et al. (Zhang et al., 2019)	Site selection	On-grid (China)	PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation)	Energy, Construction and Maintenance, Auxiliary condition, Economical, Environmental, Society
Fetanat and Khorasaninejad (Fetanat and Khorasaninejad, 2015)	Site Selection	On-grid (Iran)	Fuzzy analytic network process (ANP), fuzzy decision-making trial and evaluation laboratory (DEMATEL) and fuzzy elimination and choice expressing the reality (ELECTRE)	Depth and height, Environmental, Proximity to facilities, Economic, Technical, Culture
Latinopoulos and Kechagia (Latinopoulos and Kechagia, 2015)	Site selection	On-grid (Greece)	Siting criteria and a GIS-based approach	Technical, Economic, Social Environmental
Vafaeipout et al. (Vafaeipour et al., 2014)	Site Selection	On-grid (Iran)	Step-wise Weight Assessment Ratio Analysis (SWARA) and the Weighted Aggregated Sum Product Assessment (WASPAS)	Economic, Environmental, Social, Risk
Sánchez-Lozano et al. (Sánchez-Lozano et al., 2013)	Site Selection	On-grid (Spain)	Analytic Hierarchy Process (FAHP); Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)	Environmental, Location, Climatic, Geomorphological
Charabi and Gastli (Charabi and Gastli, 2011)	Site selection	On-grid (Oman)	Fuzzy Logic Ordered Weight Averaging (FLOWA) and an ordered weighted averaging (OWA)	Technical, Environmental, Economic
Pérez and Diaz (Pérez-Gelves and Díaz-Florez, 2020)	Site selection	Off-grid (Colombia)	Analytic Hierarchy Process (AHP)	Techno-economic, Social, and Environmental risks
Ghasempour et al. (Ghasempour et al., 2019)	Technology assessment and site selection	Off-grid (China, Iran)	Fuzzy Analytic Hierarchy Process (FAHP); Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS); Decision-making trial and evaluation laboratory (DEMATEL)	Site selection: Climate, Geographical, Orography, Transportation, Environment, Cost. Technology selection: Technical, Financial, Environmental
Haddad et al. (Haddad et al., 2017)	Technology assessment	On-grid (Algeria)	Analytic Hierarchy Process (AHP)	Technical, Economic, Environmental, Socio-political
Fuso Nerini et al. (Fuso Nerini et al., 2014)	Technology assessment	Off-grid (Amazon region in Brazil)	A direct method of Anchored Rating Scale (ARS)	Technical, Economic, Environmental, Social, Institutional
Rahman et al. (Rahman et al., 2013)	Technology assessment	Off-grid (Bangladesh)	Stochastic Multi-criteria Acceptability Analysis (SMAA-2)	Technical, Economic, Environmental, Social, Policy
Cherni et al. (Cherni et al., 2007)	Technology assessment	Off-grid (Colombia)	Sustainable rural energy decision support system (SUREDSS)	Physical, Financial, Natural, Human, Social

Fuso Nerini et al. (2014) (Fuso Nerini et al., 2014) argue that rural electrification in the Brazilian Amazon is associated with 16 criteria grouped under five dimensions, namely technical, economic, environmental, social, and institutional/political. They applied a multi-criteria approach based on a simple weighting methodology (i.e., the direct method of Anchored Rating Scale (ARS)), where decision-makers were asked to quantify their preference through a participatory process. As a result, biomass systems and solar PV systems registered the highest scores in the final index, 77%, and 76%, respectively. Ghasempour et al. (2019) (Ghasempour et al., 2019) present a review of a variety of multi-criteria decision-making techniques applied to select solar plant sites and technologies. This includes the application of Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methods, Analytic network process (ANP), Analytic Hierarchy Process (AHP), the Preference Ranking Organization Method for Enrichment of Evaluation (PROMETHEE) method, among others. Rahman et al. (2013) (Rahman et al., 2013) applied a Stochastic Multi-criteria Acceptability Analysis (SMAA) method and Monte Carlo simulation to aid the process of selecting the best option for expanding electricity access in a rural area of Bangladesh. In this case study, the author considered 24 criteria values grouped into five sustainability dimensions. As a result of this process, the solar PV and biogas plants were found as the most preferable alternatives with 59% and 41% acceptability in their first rank, respectively.

Pérez-Gelves and Díaz-Florez (2020) (Pérez-Gelves and Díaz-Florez, 2020) used the case study of Colombia to develop a methodology to assess the implementation of solar PV projects in rural areas of Colombia. They assessed all the country's departments using an AHP and considered techno-economic, social, and environmental risk dimensions. The evaluation was based on data from the National Survey on Living Conditions in Colombia (NSLCC) and the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM). A list of eight departments represented the prioritised regions to implement solar power projects in the country. Cherni et al. (Cherni et al., 2007) designed and implemented a multi-criteria sustainable rural energy decision support system (SUREDSS) to select the most appropriate set of energy options for providing sufficient power to a rural and remote community in the department of Arauca, Colombia. Based on this multi-criteria approach, they ranked the possible energy system options (i.e., Micro-hydro, solar PV, Biogas, Hybrid diesel-biogas, Hybrid diesel-solar, and Hybrid diesel-hydro) through four dimensions: physical, financial, natural, physical and human assets. As a result, the program identified the best technology option based on a total score for each possible energy alternative where the highest given rating is 1 and the lowest is 0.

Overall, there is no unique reference for the type of MCDM methods, dimensions, and criteria used to implement sustainability assessments within the rural electrification sector. This doctorate thesis uses the Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH) approach to assess the suitability of different potential off-grid sites for implementing off-grid solar PV projects, based on a set of sustainable dimensions and key criteria. MACBETH is a non-numerical approach designed to aid decision-makers to quantify the relative attractiveness of options (Bana e Costa et al., 2016). It has been successfully applied in several real-world case studies including in the area of energy technology choice (Andrade et al., 2016; Burton and Hubacek, 2007; Ertay et al., 2013; Feitosa and Costa, 2021; Montignac et al., 2009; Tosun, 2017). However, this study constitutes the first study applying the MACBETH approach to the off-grid site selection decision problem.

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3.Methods

3.1 Justification of Research Strategy and Methods

Figure 3.1 illustrates the research strategy used in this thesis. Developing each one of the methodological phases of this research required to use of a variety of qualitative and quantitative data sources, gathering techniques and analysis approaches including an extensive literature review, and a collection of in-situ evidence in the form of structured observations, and semi-structured interviews with experts and project developers.

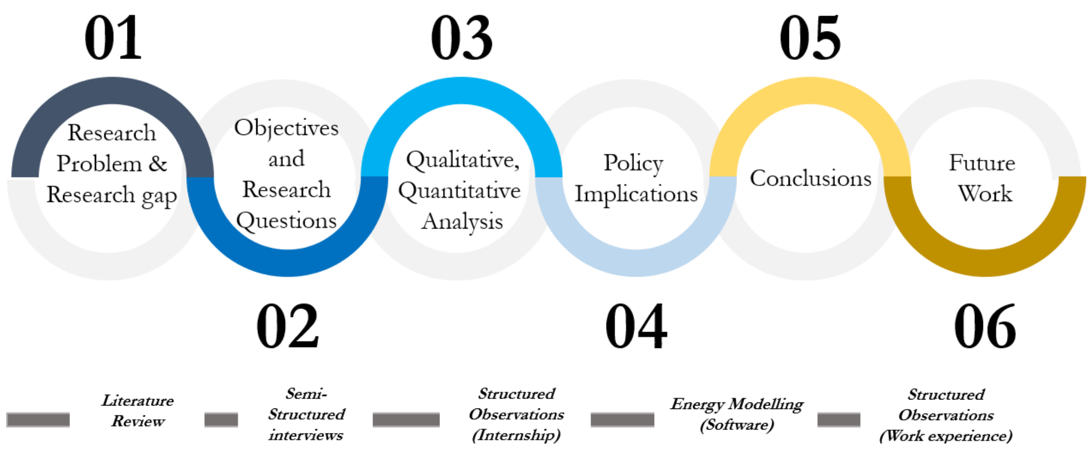


Figure 3.1 Research Strategy

The initial stage of this doctorate thesis consisted in identifying the research problem or research gap. This required understanding the main challenges related to the energy provision in off-grid areas, the regulatory framework associated with the off-grid electrification sector of developing countries, and the likely opportunities to bridge the electricity access deficit gap based on a sustainable energy planning framework. During the first and second phases, an extensive literature review considering basic concepts, theories, and previous research findings provided an understanding of the research context. As a result, the objectives and research questions were defined.

In the third phase, this thesis relied on the combination of both qualitative and quantitative approaches, the basis of the Mixed Methods Research (MMR). As Gómez (2014) (Gómez, 2014, p.8) argues: *"The MMR provides a better approach to analyse the research questions than either method alone"*. In addition, audiences such as policymakers, practitioners, and decision-makers need qualitative and quantitative evidence to document diverse research problems and make better-informed decisions (Creswell, 2014). Thus, MMR was selected as the research method for this thesis because it allows to combine and complement different research perspectives by analysing quantitative and qualitative data.

In this doctorate thesis, most publications combine several approaches based on a MMR approach, as summarised in Table 3.1.

Paper 1 elaborates on the first research question of this thesis. To provide some answers, this study mainly relies on a literature review of different multidimensional approaches used as the social criterion to allocate public funds and prioritise rural electrification projects. x. In doing so, it examines the suitability of using the unsatisfied basic needs (UBN) index, as the social criterion to target the poorest communities. The main contribution of this paper is to inform about current programs and achievements concerning the rural electrification policy in Bolivia. Additionally, it describes the association between the UBN index and the improvement in access to electricity in all the Bolivian municipalities.

Table 3.1 Main methods applied within the Mixed Method Research approach

Publication	**Case Study**	**Quantitative and Qualitative data sources**	**Method/Tool**
Electrification for the elite? Examining whether electrification programs reach the poor in Bolivia	Bolivia	Peer-reviewed papers and review on Bolivia's Censuses of 2001 and 2012, the Unsatisfied Basic Needs (UBN) index for 2001 and 2012 (339 municipalities) and electricity access rates for 2001 and 2012.	• **Literature review** (e.g. technical papers, national plans, and programs, international reports). • **Descriptive analysis** of relationship between the 2001 UBN index and the improvement in electrification rate between 2001 and 2012.
Using a Multi-Criteria Model to Assess the Suitability of Potential Sites to Implement Off-Grid Solar PV Projects in South America.	Bolivia, Peru, and Colombia	Peer-reviewed papers and semi-structured interviews with a decision-maker from the private sector	• **Literature review** • **Modelling:** MCDM using the MACBETH approach to evaluate the performance of each option with the inputs from a DM.
Lowering risk intolerance to unlock private investments in renewable energy-based rural electrification	Colombia	Estimates of the total costs and revenues derived from the literature review (Vides-Prado et al., 2018) and semi-structured interviews with off-grid providers.	• **Literature review** • **Semi-structured interviews** involving three experts in energy planning and rural electrification projects: • **Business risk analysis:** Costs and revenues comparison • **Investment risk analysis:** main measures of risk (Expected NPV comparison, Std. Dev, VaR), using Monte Carlo simulation, and Sensitivity Analysis • **Risk identification and assessment process**: Risk Map
Efficiency for access: the role of high-performing appliances as a potent catalyst of scaling energy access in off-grid areas.	Colombia	Data from the residential socio-economic and electricity consumption survey (RESC) of La Guajira, including 1255 responses across 15 municipalities.	• **Descriptive Analysis** of the relationship between appliance ownership (fans and refrigerators) and electricity access • **Appliance ownership diffusion modelling** to capture key household appliance ownership drivers such as Household income, Index of rurality, and Electricity access.
Achieving Universal Access in the off-grid areas of Colombia: challenges and policy implications. Energy Policy	Colombia	Two groups of data sources: 1) Specialised technical papers and academic publications; 2) reports from public institutions of Colombia's energy sector.	• **Literature review** of the main challenges that historically have hindered the Colombian electrification efforts towards universal access. • **(11) Semi-structured interviews** (between 2019 and 2021, at virtual or presence meetings) with different stakeholders directly related to the off-grid electrifications sector in Colombia, such as utility companies, off-grid energy service providers, academia, and the public sector.
How rural electrification efforts can benefit from the implementation of minigrids systems? (forthcoming). *Microgrids as an alternative energy solution for off-grid rural areas in Colombia.*	Colombia	Solar and Wind energy Atlas Investment and O&M costs for diesel-based projects and off-grid RE-based projects	• **Literature review** (e.g. technical papers, national plans, and programs, international reports). • **Modelling:** LCOE model • **Software Simulation:** HOMER

Multidimensional approaches such as the BNA are widely used in developing countries, including Latin America (Hicks, 2000). In particular, the BNA, grounded on Rawls' Theory of Justice (1971), focuses on defining a set of primary goods/services that are constituent elements of well-being and considered necessary to live a good life (Streeten et al., 1981). It was first introduced by the United Nations Economic Commission for Latin America and the Caribbean (CEPAL in Spanish) in the 80s, to build up poverty maps, showing the lack of access to basic services, based on the information obtained from the local Censuses (Santos, 2014). It is also referred to as a direct method to measure poverty because it observes and evaluates whether a household has or does not have the goods and services that effectively satisfy its basic needs. It relates wellness with real access to basic services, such as water, sanitation, electricity, education, and health (Andersen and Jemio, 2016; Feres and Mancero, 2001). Likewise, the BNA is considered a counting approach to identifying the poor because it entails *"counting the number of dimensions in which people suffer deprivation"* or *"the number of dimensions on which they fall below the threshold"* (Santos, 2014, p.51). To measure this level of deprivation, the BNA relies on the Unsatisfied basic needs (UBN) index, a composite of the indicators' scores measuring the degree of satisfaction with basic needs. Based on the UBN index, the poor are those who experience at least one deprivation or the proportion of households unable to satisfy one, two, three, or more basic needs (Feres and Mancero, 2001; Santos et al., 2010).

One of the limitations of this approach is that *"it may identify as poor people who are not poor, given that deprivation in one dimension may be due to reasons unrelated to poverty such as behavioural exceptions (for example, a person deciding, of his own free will, to live in a house built with austere materials, regardless of a high level of education, formal employment or generally good living conditions)"* (Salazar et al., 2013, p.5).

On the other hand, the HDI has been used to estimate and compare countries' development. This index measures the achievements of human development in three key dimensions: a long and healthy life (i.e. life expectancy at birth), access to knowledge (i.e. expected years of schooling and mean years of schooling), and a decent standard of living.

More recently, South American countries are using the Multidimensional Poverty Index (MPI) to set targets to close the country's poverty gaps and second, to track progress toward them. Examples of official permanent national MPIs include Colombia (launched in 2011), Chile (launched in 2015), and Ecuador (launched in 2016). The MPI was released in 2010 by the Oxford Poverty & Human Development Initiative (OPHI) (Santos et al., 2015) and also builds on the counting traditions (such as the UBN index), but it combines monetary and non-monetary indicators, not typically measured in Latin America, through the traditional UBN index (Santos, 2014). In particular, the MPI is an internationally comparable index to measure acute poverty across three dimensions: Education (years of schooling and school attendance), health (child mortality and nutrition), and standard of living (cooking fuel, sanitation, access to water services, access to electricity, floor, and assets ownership). Under this approach, a person is multidimensionally poor if he or she is deprived of at least one-third of the weighted indicators, requiring a household to be deprived of multiple indicators at the same time (OPHI, 2018).

One of the main advantages of using the MPI is to provide data on multidimensional poverty not only at the national level, but also the MPI can be 'decomposed' by sub-national regions to show disparities in poverty within countries by ethnic group, urban/rural area, and age group, as well as other key household and community characteristics. The MPI also innovates with respect to previous poverty measures in the region, in three ways. First, *"it combines monetary and non-monetary indicators. Second, among the non-monetary indicators, it updates the deprivation cut-offs of the traditional* UBN *indicators to better align them with current living standards. Third, it goes beyond the traditional* UBN *indicators by including deprivations in the employment and social protection as well as the schooling gap"* (Santos et al., 2015, p.4). In particular, the MPI developed by the Colombian Government and implemented by the national planning department presents the way this measure can be used to help inform, monitor, and evaluate poverty reduction strategies (Santos et al., 2015). This thesis indicates that using complementary socio-economic indicators, such as the Multidimensional poverty index (MPI), could complement the traditional UBN index by capturing more relevant information that could lead to a more accurate poverty measurement and rural electrification interventions. This analysis could be used as a reference not only in Bolivia but also in other developing countries relying on the UBN index.

Paper 2 is a response to the research question (RQ) 3 and conducts a detailed review of the peer-reviewed empirical literature associated with multi-criteria decision-making (MCDM) analysis and sustainability assessment. Based on the current literature, this paper implements the MACBETH approach to assist in the selection of the most suitable location to implement off-grid solar PV projects in South America, accounting for different sustainability dimensions derived from a participatory process with a decision-maker from the private sector. This analysis is relevant because potential investors and project developers face the decision problem of deciding where to invest in rural and remote areas while guaranteeing the sustainability of rural electrification projects in the long-term view (Eras-Almeida et al., 2019), namely the *"capability of the project to be continually operational over its useful lifespan"* (Louie et al., 2014, p.71). This site selection decision-making process can be considered a complex task because it requires accounting for different factors (qualitative and quantitative) that influence the selection of a potential off-grid site over other alternatives (Aldrin Wiguna et al., 2017). Thus, a multi-criteria analysis is useful to address this multi-faceted decision problem while accounting for multiple dimensions (Cherni et al., 2007; Rahman et al., 2013).

As presented in Chapter 2, in the literature, there is a variety of MCDM methods that support different rural electrification decision-making processes (Cherni et al., 2007; Fetanat and Khorasaninejad, 2015; Fuso Nerini et al., 2014; Ghasempour et al., 2019; Haddad et al., 2017; Latinopoulos and Kechagia, 2015; Pérez-Gelves and Díaz-Florez, 2020; Rahman et al., 2013; Sánchez-Lozano et al., 2013; Vafaeipour et al., 2014; Zhang et al., 2019). In particular, these multi-criteria approaches are mainly incorporated in two types of studies: (1) studies that apply a technology assessment to select the most appropriate technology for energy provision in rural communities based on the attributes that each potential technology exhibits (Charabi and Gastli, 2011; Fetanat and Khorasaninejad, 2015; Latinopoulos and Kechagia, 2015; Pérez-Gelves and Díaz-Florez, 2020; Sánchez-Lozano et al., 2013; Vafaeipour et al., 2014; Zhang et al., 2019); (2) studies that evaluate potential site alternatives to implement rural electrification projects based on different criteria (Cherni et al., 2007; Fuso Nerini et al., 2014; Haddad et al., 2017; Rahman et al., 2013). In both scenarios, the sustainability assessments require accounting for a set of criteria that are related to the SDGs and cover multiple dimensions of sustainability (Marques et al., 2015). Some authors refer to these dimensions as 'criteria', a term that finds correspondence in the "set of factors that may be used to assess which of a range of options offers the greatest contribution to achieving sustainability objectives" (Ashley et al., 2004).

Unlike other existing methods that assist rural electrification decision-making, the MACBETH approach uses a simple dialogue process in which the decision-maker (DM) carries out pairwise comparisons and gives only qualitative judgements about the differences in preferences of certain options (Bana e Costa et al., 2012, 2008; Marques et al., 2015) As a result, this procedure may be suitable for a DM who does not like to quantify preferences or to express his preference judgements numerically. Also, a particularly useful aspect is that MACBETH allows graphical representations of the performance profiles of the assessed options, making it possible to visually compare the attributes of each alternative in each criterion.

One of the limitations of this approach appears when evaluating more than five options. When the number of options (or the level of descriptors) is high, the MACBETH method might become an exhausting process for the DM, who must provide judgements of the difference of attractiveness between all the possible options and thus, resulting in a time-demanding process. It is also worth mentioning that some of the methodological steps followed in this study are not exclusive to the MACBETH methodology, such as the procedures for developing and validating constructed descriptors of performance. Instead, they can be combined with other value function assessment approaches. Doing so, however, may sacrifice the added value of using a qualitative pairwise comparison approach.

Paper 3 is linked to RQ2 and employs both, qualitative and quantitative research methods. It first identifies the main uncertainties and the potential derived risks that can affect the outcome of an off-grid electrification project, based on the literature review and semi-structured interviews involving three experts in energy planning and rural electrification projects. Then, using a Risk Map, a risk assessment is performed to evaluate the Impact and Probability of each potential risk event, based on the provided input of a DM.

Regarding the quantitative approach, this paper quantifies the business and investment risks associated with the project under analysis, using a stochastic discount cash flow technique —the net present value (NPV) combined with Monte Carlo simulation. Traditionally, investment projects in electrical networks are prioritised based on their expected profitability as measured by the NPV (Verdelho et al., 2016). In the rural electrification sector, other authors have used this criterion to assess and select the optimal technology solution to be installed in off-grid areas. In the Colombian context, Haghighat Mamaghani et al. (2016) and Vides-Prado et al. (2018) (Haghighat Mamaghani et al., 2016; Vides-Prado et al., 2018) performed a techno-economic feasibility study to compare different RE systems, considering the NPV, the initial capital cost, and the cost of energy as economic indicators. Vides-Prado et al. (Vides-Prado et al., 2018) sized and conducted a techno-economic comparison of solar PV systems to be installed in different indigenous communities located in remote areas of La Guajira, Colombia. Mamaghani et al. (Haghighat Mamaghani et al., 2016) modelled and optimised different combinations of solar PV, wind, and diesel generation to determine the most energy-efficient and cost-effective configuration for three off-grid locations in Colombia: Unguia, La Guajira, and Narino.

In this case, this paper uses the NPV as the evaluation criteria to determine if the selected project represents a business opportunity for the private investor, namely if value is added to the company if the project is implemented. Figure 3.2 illustrates the influence diagram of the project financials considered in this study, showing the dependencies and relationships between variables (some of them representing uncertainties) that yield to estimate of the NPV.

Formally, the NPV is expressed as presented in Equation (3.1).

$$NPV = \sum_{t=0}^{n} \frac{FCF_t}{(1+k)^t} = \sum_{t=0}^{n} \frac{R_t - C_t - I_t}{(1+k)^t} \qquad \text{Equation (3.1)}$$

Where FCF_t is the free cash flow at year *t*, *Rt* are the revenues at year *t*, C*t* are the total costs (fixed and variables) at year *t*, *It* is the investment at year *t*, *n* is the time horizon of the investment project and *k* is the discount rate. If the NPV is greater than zero, it is expected that value will be created for the investor. Otherwise, if the NPV is less than zero, the value of the resources used by the project is greater than the value of the benefits the project creates. Results of the estimated NPV for this study is presented in the appendix section (Table A2).

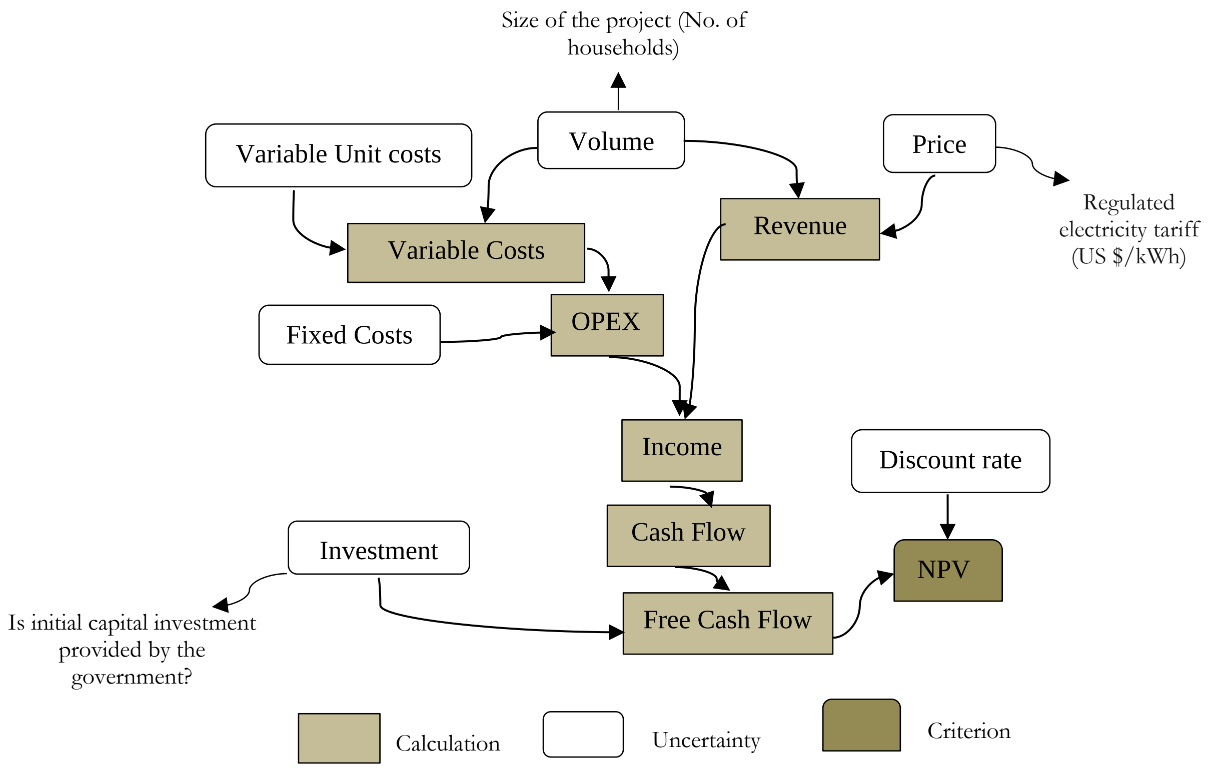


Figure 3.2 Influence diagram with main variables of the project financials. Source: Authors' own from (Crundwell, 2008)

This process is repeated numerous times to determine the output of the model, namely the probability distribution for the NPV. As a result, the distribution of the outcome provides the expected NPV of the project or its stand-alone risk. In addition, this study uses three measures of business risk to provide a recommendation on the project: the standard deviation of the NPV, the coefficient of variance (CV), and the value at risk (VaR). The standard deviation for the free cash flow for each year, $\sigma FCF,t$, is composed of independent contributions from the revenues, costs, and investments, leading to the annual variance (σ^2) given by Equation 3.2.

$$\sigma^2 = \sum_{t}^{n} \frac{1}{(1+k)^{2t}} \sigma^2_{FCF,t} \qquad \text{Equation (3.2)}$$

With,

$$\sigma^2_{FCF} = \sigma^2_{R,t} + \sigma^2_{C,t} \qquad \text{Equation (3.3)}$$

Where $\sigma^2_{R,t}$ and $\sigma^2_{C,t}$ represent the variances in year t for the revenues and costs. The analysis presented in this chapter considers that changes in the cash flows in each year are independent of one another, then the correlation coefficient is equal to zero.

The coefficient of variance (CV) allows investors to determine how much volatility or risk is assumed in comparison to the amount of return expected from investments. The lower the CV, the better the risk-return trade-off. Mathematically, CV is defined as the ratio between the standard deviation of the NPV and the expected value of the NPV, as presented in Equation 3.4).

$$CV = \frac{\sigma}{\overline{\overline{NPV}}} \qquad \text{Equation (3.4)}$$

Finally, in order to assess the chances of the project failing, namely the probability of having a negative *NPV*, i.e., P(*NPV* < 0), the value at risk or *VaR* of the project was estimated. This probability is determined from the cumulative frequency plot for the NPV, which reproduces the probability mass function, and represents the probability that a random variable *X* will be less than a certain value *x*, that is P*(X < x)* (Crundwell, 2008).

As presented in Figure 3.2, when estimating the NPV, some variables are known with certainty, and other variables are known within a particular range, namely uncertainties representing a quantity or variable about which the decision-maker or the company has no control (Crundwell, 2008). This is the case in the off-grid electrification sector, where companies have to adapt the discounted cash flow techniques (e.g. the NPV) to the probability of negative events affecting their investments and profits. As highlighted in Figure 3.2, the main uncertainties influencing the outcome of the project financials under analysis, are the variability in the variable costs, the fixed costs, the revenue, the market size (volume), the price, the investment, and the discount rate.

This unpredictability or change of the constituents of the project financials is a source of risk for a project (Crundwell, 2008). In this paper, the analysis is based on the framework proposed by McManus and Hastings (McManus and Hastings, 2005), which aims at understanding the wide range of uncertainties that can appear during the design, implementation, and use of complex systems and their relationships with system risks which affect the desired outcomes. Thus, this study not only identifies the main uncertainties influencing the outcome of the project but also assesses and quantifies the risks that this project may bring to the company.

Risk assessment is important for two reasons (Crundwell, 2008): 1) the value of the project may differ from what it was forecast to be and this type of risk represents a loss to the owner of the project, and 2) the risk of the project contributes to the risk of the company and the risk of the investors in the company. According to the ISO 31000 standard "Risk Management", managing risk depends on establishing the context and continues through sections of risk assessment, risk treatment, recording and reporting, monitoring and reviewing, and communicating and consulting (ISO, 2022). This study is focused on the risk assessment process, including risk identification, analysis, and evaluation.

According to (Crundwell, 2008), the NPV variability contributes to business risks, financing risks, and investment risks. Business risk refers to any change in the revenues and the operating costs of the project from normal operations, resulting in variability in the earnings of the company. Investment risk is defined as the change or variation in the estimate of the initial capital expenditure to build and install the project. Finally, financing risk refers to "the variability in the profit as a result of changes in the interest rate that affect the company's ability to meet its debt commitments" (Crundwell, 2008).

Since the deterministic NPV values fail to capture the natural variability that occurs in the project financials due to the variation of some input variables, it is necessary to use other methods to assess and quantify the risks associated with an investment project. In the literature, there are mainly found four methods of incorporating and quantifying these risks into the analysis of a project's value: the probability method, the certainty equivalent method, the risk-adjusted discount rate method, and the Monte Carlo simulation (Crundwell, 2008). This paper relies on the Monte Carlo method to draw random samples from the probability distributions of the main uncertain variables (i.e. drivers of risk). This process is repeated numerous times to determine the output of the model, namely the probability distribution for the NPV. As a result, the distribution of the outcome provides the expected NPV of the project or its stand-alone risk. In addition, this paper uses three measures of business risk to provide a recommendation on the project: the standard deviation of the NPV, the coefficient of variance (CV), and the value at risk (VaR).

Paper 4 relies on qualitative research methods that incorporate a literature review combined with semi-structured interviews. The literature review analysis relies on two groups of data sources: 1)

Specialised technical papers and academic publications; 2) reports from public institutions such as the Ministry of Mines and Energy (MME), the Institute for the Planning and Promotion of Energy Solutions in the ZNI (IPSE), the Planning Unit on Mining and Energy (UPME), and the National Planning Department (DNP). In addition, the second part of the analysis is based on a participatory process that resulted in eleven (11) semi-structured interviews with different stakeholders (i.e. directly related to the off-grid electrifications sector in Colombia, such as utility companies, off-grid energy service providers, academia, and the public sector (See Chapter 5). This paper utilises information that was elicited in directed discussions between 2019 and 2021, at virtual or in-presence meetings.

Paper 5 and 6 employs an energy system modelling, based on a simple LCOE model that determines the optimal electricity supply technology for a certain location, considering the load requirements of the community under analysis, maximizing the use of available renewable resources, and minimizing the use of fossil fuels to provide the optimal system cost, emissions levels, and the electricity cost. The LCOE has been widely used in the literature to compare different energy generation technologies within the rural electrification context (Haghighat Mamaghani et al., 2016; Vides-Prado et al., 2018; Villota, 2015). Authors in Haghighat Mamaghani et al. (2016) (Haghighat Mamaghani et al., 2016) modelled and optimised different combinations of solar PV, wind, and diesel generation to determine the most energy-efficient and cost-effective configurations for three off-grid locations in Colombia: Unguia, Puerto Estrella, and Jerico. As a result, the combination of diesel, solar PV, and wind turbines, was the optimal option in Puerto Estrella, while in Unguia and Jerico, a solar-diesel system led to the most economically convenient design. Vides-Prado et al. (2018) sized and conducted a techno-economic comparison of solar PV systems to be installed in different indigenous communities located in remote areas of La Guajira, Colombia.

In this doctorate thesis, the energy modeling software HOMER (Hybrid Optimization Model for Electric Renewables) Pro 3.14.1 software was used to simulate different hybrid off-grid energy systems compared with a system that runs with a diesel generator. Each minigrid was modelled considering the following input data: i) the demand profile for each community; ii) The project location, from which the software obtains the available energy resource data; iii) The investment and O&M costs of the proposed system; iv) The lifecycle of the equipment and elements to be simulated; v) Technical specifications of the different generation technologies; vi) a multi-year analysis with demand growth of 2.6% and vii) expected renewable fraction of the system. The main objective of the model is to minimise the annual cost of supplying electricity ($/kWh) to a certain community, considering the optimal design of different potential minigrid technologies, categorised as renewable and conventional resources (i.e. solar PV, wind, diesel) while accounting on different constraints, as formulated in Equation 3.5.

$$minLCOE\ (MGtech_i)\ \forall\ i = 1,2,3,\dots,MGtech_{options} \qquad \text{Equation (3.5)}$$

Constraints:

i) Load constraint: The load demanded should be supplied in all conditions:

$$\sum_{j=1}^{15} (P_{MGtech_i}) = Demand_j \qquad \forall\ i = 1,2,3\dots,totalMGtech_{options} \qquad \text{Equation (3.6)}$$

ii) Renewable fraction < (75%; 85%)
iii) Minimum autonomy of 12 hours of system
iv) Excess power no more than 10% of the main load
v) Battery autonomy= 24 hours
vi) Battery discharge rate of not less than 50%.

The LCOE can be formulated as presented in Equation 7.3 and depends on the annualized cost of producing electricity $C_{\text{ann,tot}}$ (\$/year) and the total electric load served E_{demand} (kWh/year) (HOMERenergy, 2022), namely:

$$LCOE_{alternative} = \frac{C_{\text{ann,tot}}}{E_{demand}} \quad \text{Equation (3.7)}$$

Estimating $C_{\text{ann,tot}}$ depends on the following equation:

$$C_{\text{ann,tot}} = (CRF)(NPV) \quad \text{Equation (3.8)}$$

where CRF is the capital recovery factor:

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \quad \text{Equation (3.9)}$$

where N and i are the system lifetime and the annual real discount rate, respectively.

Paper 7 combines qualitative and quantitative methods. The first part employs a descriptive analysis derived from observed trends in appliance ownership and electricity access in rural areas of La Guajira, Colombia. It relies on data from the residential socio-economic and electricity consumption survey (RESC) of La Guajira, including 1,255 responses that were analysed using the statistical software platform IBM® SPSS® (Chaves and Villota, 2016). The second part implements an econometric diffusion analysis, based on a multiple linear regression model to identify the most statistically significant indicators of appliance ownership in rural areas with the current electricity service of La Guajira, Colombia.

The appliance ownership diffusion is modelled as a S-shaped function, using a logistic function, as suggested in (McNeil and Letschert, 2010). According to Diawuo (Diawuo, 2020), the logistic model effectively captures consumer choice and thus, it is appropriate for the econometric modelling of a simple binary choice model. Based on this approach, Equation (3.10) and Equation (3.11) are used to estimate the ownership of an appliance at a specific level of electricity access, income, and index of rurality. This analysis uses the Root Mean Square Error (RSME), which predicts the error between the real and the modelled data, to ensure the accuracy of the model, as expressed by McNeil and Letschert (McNeil and Letschert, 2010).

$$Diff_m = \frac{\alpha}{1 + \gamma e^{(\beta_{inc} I_m + \beta_{elec} EA_m + \beta_{rul} RI_m)}} + \varepsilon \quad \text{Equation (3.10)}$$

Where, $Diff_m$ is the diffusion of the appliance for each municipality (m) of La Guajira department; α is the saturation level; I_m is the household income given by GDP per capita; EA_m is the electricity access rate; and RI_m corresponds to the index of rurality in each municipality. The electrification and the index of rurality range between 0 and 1, while income is unbounded.

The logistic function defined in equation (1) has a maximum of one, at which point saturation is reached. In this model, the logistic function is scaled by the parameter α, which is the saturation level. This value represents the current maximum observed ownership of the appliance and in this case, reported in the residential household survey.

After defining the saturation level for each appliance, the logistic diffusion function can be converted to a linear function, and thus, a multiple linear regression (MLR) method is used to analyse the data. As presented in McNeil and Letschert (2010), the mathematical formulation of equation (3.10) can be transformed into Equation (3.11):

$$\ln\left(\frac{\alpha}{Diff_m} - 1\right) = ln\gamma + \beta_{inc}I_m + \beta_{elec}EA_m + \beta_{rul}RI_m + \varepsilon \qquad \text{Equation (3.11)}$$

Overall, this third stage of the research strategy was supported by a field visit to La Guajira (Colombia), the Country's municipality with the highest deficit in electricity access was conducted in rural and remote indigenous communities. This fieldwork was part of a three-month internship done at Kingo Energy (i.e. a Guatemalan off-grid energy provider with operations in rural areas of Guatemala and Colombia) during the Spring term of 2020. As a result, structured observations provided an opportunity not only to observe communities and obtain information on their living conditions and energy needs in their natural environment but also to obtain perceptions of private companies and project developers on the technical and financial lessons from implementing off-grid projects in Colombia. Within this stage, semi-structured interviews with experts in energy planning and off-grid project development were also a useful research tool.

Finally, based on the main findings derived from this thesis, stages 4 to 6 present the main contributions and the need for further research to expand on aspects of this dissertation. Also, indicative insights for policymakers are proposed.

Overall, within the MMR approach, this thesis encompasses case studies in Bolivia, Peru, and Colombia. It also relies on mainly five groups of data sources: the first group included household representative data from Bolivia's and Colombia's Censuses and the National Households surveys, which contain information on socio-economic variables for each country's municipalities, including electricity access rates. The second group comprised National reports and academic publications such as specialized technical papers, Master's and Ph.D. theses developed by local universities. The third group corresponded to reports from local electricity companies and information from local government institutions such as the Ministry of Mines and Energy. The fourth group of sources comprised data from international institutions involved in electricity access programs including reports from the World Bank, the International Energy Agency (IEA), the United Nations Development Program (UNDP), and the Inter-American Development Bank (IDB). Finally, the fifth group comprised semi-structured interviews involving different stakeholders involved in the off-grid electrification sector and the energy planning of rural areas in developing countries.

4.Closing the electricity access gap: A review of case studies

This chapter describes the national rural electrification policies developed in recent years to provide universal electricity access in Bolivia and Peru. The chapter analyses the achievements of each country's national programs in the light of institutional, technology, and funding structures. It highlights the essential role of promoting a decentralised energy solutions approach in reaching the last-mile rural communities and, cross-country lessons are presented. In both cases, despite remarkable results, rural electrification public efforts are not enough to provide electricity for all by 2030. Thus, private sector participation and investment are required.

Bolivia and Peru have one of the lowest rural electrification rates in South America (OLADE, 2022). Local governments' initiatives and association with private institutions and external donors have managed to considerably increase the National electrification rates, rising from about 65% of the population in 2000 to more than 90% in 2020, as presented in Figure 4.1. However, additional interventions in rural electrification initiatives are required, to reach a 100% electrification rate by 2025 (Peru) and 2030 (Bolivia), in compliance with the SDG 7.

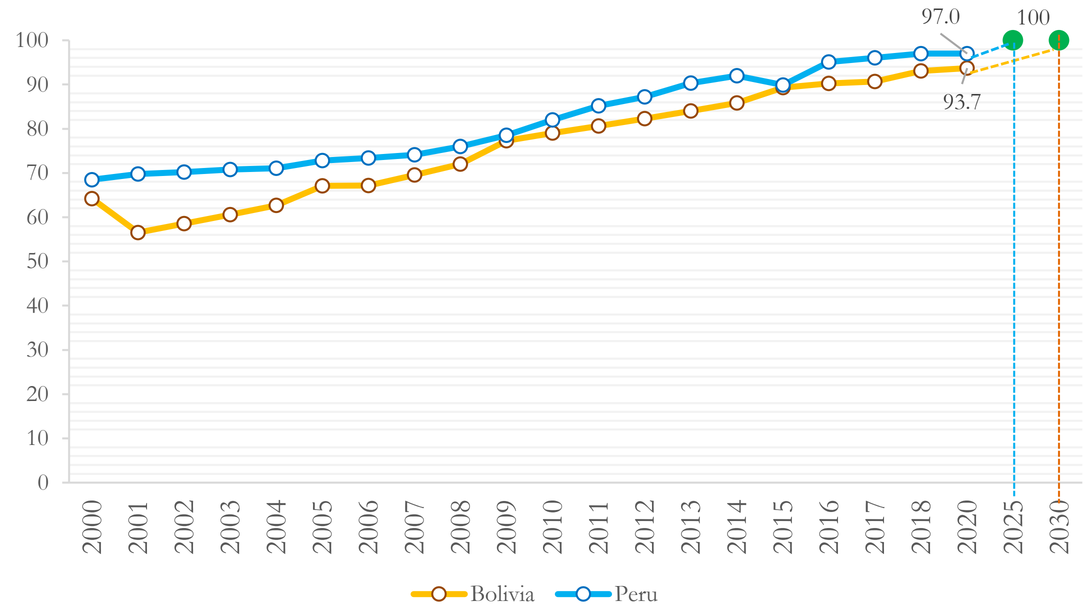


Figure 4.1 Electrification rates in Bolivia and Peru between 2000 and 2020. Source: (OLADE, 2022).

4.1. Bolivia

Following the existing literature, there is little empirical evidence evaluating the rural electrification policy in Bolivia, the country with the lowest electrification rate in the Amazon Region and which has historically been among the three South-American countries with the lowest rural electrification rate (World Bank, 2014). How is the Bolivian rural electrification policy progressing towards meeting universal access? To provide some answers, this chapter presents an overview of Bolivia's rural electrification policy. It provides a general overview of the current programs and achievements concerning the rural electrification policy in Bolivia. Additionally, key lessons derived from rural electrification programs implemented in remote communities of Bolivia are highlighted.

4.1.1. Bolivia's National Rural Electrification Policy

The Bolivian electric power system consists of the National Interconnected System (NIS), which serves the main cities of the country, and the off-grid system (OS), which provides electricity to scattered or distant communities (See Figure 4.2) (INE, 2016). This electricity infrastructure, managed by the Ministry of Energies (ME), serves about 2,760,326 households, representing a national electrification rate of about 90.3% (as of 2016) (VMEEA, 2008a).

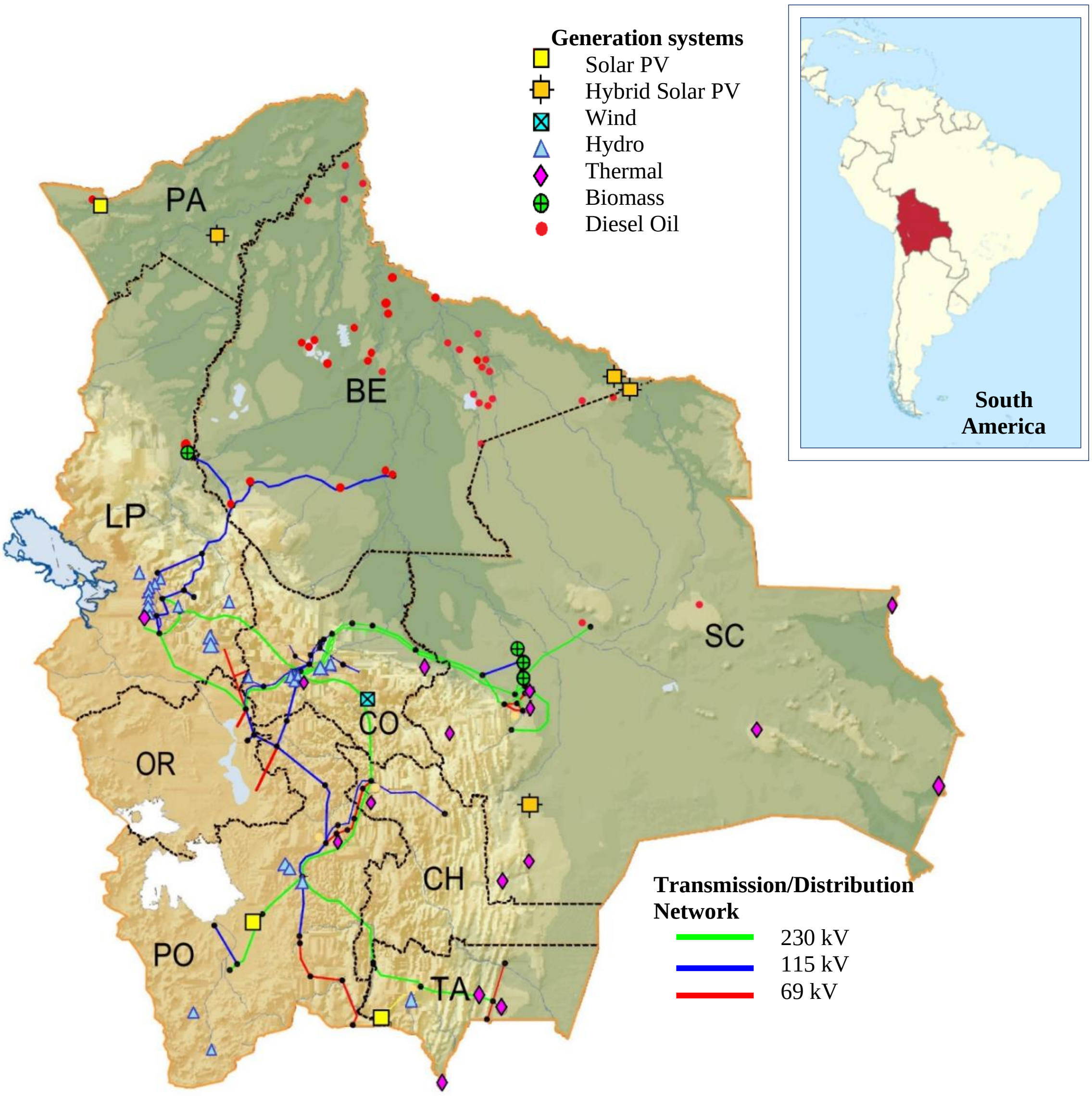


Figure 4.2 Interconnected and off-grid electricity systems in Bolivia (2018) covering the states of: PA (Pando), BE (Beni), SC (Santa Cruz), OR (Oruro), LP (La Paz), PO (Potosi), CH (Chuquisaca), TA (Tarija), and CO (Cochabamba). Source: Authors, adapted from (Ministerio de Energías, 2017).

The total installed capacity of the Bolivian electricity system is about 2,141.09 MW (as of December 2016), 85.65% derived from the NIS and 14.35% from the OS (INE, 2016). The NIS comprises the generation, transmission, and distribution systems, and serves all the country's nine states except for Pando. Its energy matrix (as of 2016) is 80.02% based on thermoelectric generation (mainly natural gas); 19.58% comes from hydro-power plants and about 0.4% from renewable energy systems (mainly Biomass) (INE, 2016). In contrast, 80.6% of the electricity generation in the OS, depends on thermoelectric generation (about 70% is diesel-based) (UNDESA, 2013); 0.7% corresponds to hydropower generation and about 18.74% comes from solar PV and biomass systems.

The government of Bolivia (GoB) acknowledges that rural electrification is the basis for rural development and considers it one of the priority issues in the energy policies of the VMEEA (Vice Ministry of Electricity and alternative energy), the national institution responsible for establishing and facilitating rural electrification policy (Lokey, 2012). Electrification access rates show that rural electrification has increased from 33% in 2005 to 73% in 2016 (See Figure 4.3), representing about 745,912 new households with electricity access (UNDESA, 2013; VMEEA, 2014). However, Bolivia is still the country in the Amazon region with the lowest rate of rural electrification followed by Peru and Colombia, as of 2018 (World Bank, 2018). Under this circumstance, the country's electrification efforts have evolved in the last decades and several programs have been implemented to provide better coverage.

In particular, in 2002, the government established Bolivia's Rural Electrification Plan (PLABER in Spanish) to increase access to electricity in rural areas from 24.5% (in 2001) to 45% (in 2007) and thus, contributing to the socio-economic development of rural areas through access to electricity and its efficient and productive uses. The short-term goal of the program was to make 200,000 new connections within this period, but, due to political and economic crises, about 20,000 households did not get the service (Unidad de Análisis de Políticas Sociales y Económicas (UDAPE), 2015).

Then, by 2008, the VMEEA launched the Electricity Program "Living with Dignity" (Electricidad para Vivir con Dignidad or PEVD in Spanish), through the Supreme Decree No. 29635, a plan to promote universal access in urban and rural areas, giving national priority to rural electrification (VMEEA, 2008b). It focuses on reducing poverty, enabling a productive economy, providing electricity access for all by 2025, and fostering the use of renewable energy in rural and urban areas (VMEEA, 2008a). This program has contributed to bringing electricity service to about 2,303,144 households, involving the participation of the local government and the private sector.

As part of the PEVD, the government defined eight projects (See Table 4.1) being implemented in 88 municipalities and expected to benefit around 70,000 families, within four stages (Smart Villages Initiative, 2016; VMEEA, 2008a):

- *Stage I (2006-2010):* increasing electricity access rates from 33% to 53% in rural areas and from 87% to 97% in urban areas;
- *Stage II (2011-2015):* achieving an electricity coverage of 70% in rural areas and 100% in urban areas;
- *Stage III (2016-2020):* achieving an electricity coverage of 87% in rural areas;
- *Stage IV (By 2025):* achieving universal access

The first six projects were completed from 2011 to 2018, and currently, two more are being implemented, as presented in Table 4.1.

It was in 2009 when the Political Constitution of Bolivia defined electricity access as a citizen's fundamental human right (Art.20) and created a set of social initiatives to reduce the gap in energy access between urban and rural areas(Pansera, 2012). In consequence, within this effort to achieve universal access, in 2013, the government set Bolivia's "Patriotic Agenda of the Bi-century 2015-2025" targeting social and economic development under a five-year development plan (2016–2020). This program contains national goals in 13 categories, including the eradication of extreme poverty and 100% coverage of electricity (Ministerio de Planificación y Desarrollo, 2013).

Additionally, in 2014, the government launched the 2025 National Plan for the Bolivian electricity sector. It aims at ensuring the supply of electricity in the short-, medium-, and long-term to households and social/official institutions (namely schools, health centres, and community centres) in the country (VMEEA, 2014). Within the plan, there are three possible electrification options for urban and rural areas: grid densification[1], grid extension, or implementing off-grid systems. In urban areas, where the population density is high and customers are close to the main grid, the plan favours

[1] The purpose of this component is to provide electricity to users located outside the 100 m obligatory service area of distribution companies in rural and peri-urban areas, by switching from one to three-phase electrical distribution systems.

grid densification in 100% of the projects. In rural areas, 70% of the projects will depend on extending the grid, 20% on grid densification, and 10% on the installation of off-grid renewable energy systems, including minigrids and stand-alone generation systems.

Based on the projections of this national policy, achieving universal access by 2025 will imply providing electricity to about 1,484,953 households (563,841of them will be in rural areas), 210 health centres, 1,400 schools, and 310 community centres (VMEEA, 2014). This effort requires a total investment of about $US 1,986 million (VMEEA, 2014).

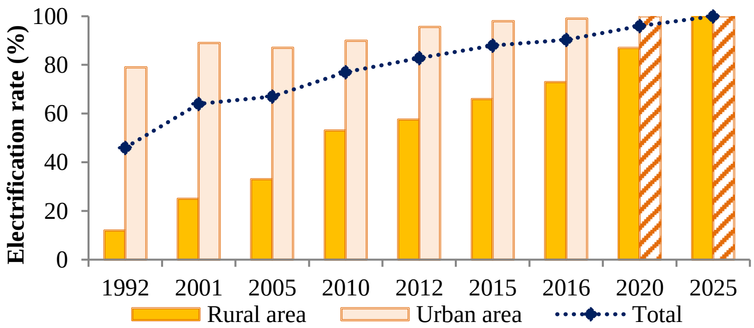


Figure 4.3 Comparison of rural, urban, and national electrification rates between 1992 and 2025. Figures for the years 2020-2025 are projections from the ME. Source: Author's own from: (UNDESA, 2013; VMEEA, 2014)

However, the average cost to provide access to electricity per household depends on the technology option and differs between rural and urban areas. In urban areas, the average cost required to provide access to electricity through grid densification is about $US 730 per household. This value contrasts with the average cost for rural areas, which is above $US 1,800 when considering extending the grid or $US 1,560 in the case of implementing off-grid renewable energy systems (VMEEA, 2014). As of 2016, urban areas already achieved 99% of electricity coverage, through the densification of the distribution grid. But, in rural areas, as of 2016, 27% of the rural population still lacked access to electricity, and full coverage is only projected to be attained by 2025 (VMEEA, 2008a).

Table 4.1 Overview of rural electrification initiatives within the PEVD between 2011 and 2021. Source: Author's compilation based on (AE, 2016; Energising Development (EnDev), 2018; Ministerio de Energías, 2017; Ministerio de Hidrocarburos & Energia, 2014; Ministerio de Hidrocarburos y Energía, 2013; Nordic Development Fund and Inter-American Development Bank (IDB), 2014; Smart Villages Initiative, 2016).

Period	Project	Features	Location	No. of beneficiaries	Investment ($ US)	Source of financing
2016-2019	"Reaping life, sowing light" (Energy component) (Cosechando Agua, Sembrando Luz)	*Solar PV systems for households, education institutions, and health centres	(3) Municipalities (Tacobamba, Ocurí and Ravelo) in the state of Potosi	1524 families, 36 education institutions and health centres	10 M	Fondo Financiero para el Desarrollo de la Cuenca del Plata (FONPLATA)
2015-2016	Program of Solar PV and thermal systems in Health centres of the State of Pando *(Sistemas Fotovoltaicos y Termosolares en Puestos de Salud Departamento de Pando-SFT)*	*Installation of 21Thermal and 21 Solar PV Systems in health centres	State of Pando	21 Health centers	0.188M	VMEEA
2014-2021	Decentralized Infrastructure for Rural Transformation II *(Proyecto de Infraestructura Descentralizada-IDTR II)*	*Grid extension and grid densification *Solar PV systems for households and 138 Public institutions: schools and health centres	States of Potosi and Chuquisaca	27000 (expected)	54M	Local government (Potosi and Chuquisaca) and the World Bank
2014-2018	Access to modern energy sources Project *(Acceso a Fuentes de Energía Moderna-AFEM)*	*Installation of Pico PV solar systems	(14) Municipalities in the State of Pando	5500 (expected)	1.3M	VMEEA and Government of Denmark
2013-2018	Renewable Energy Program *(Programa de Energía Renovable)*	*Implementation of 17 micro hydropower systems	*Under Operation (156.8 kW)* in the statesof La Paz (Inquisivi), Potosi (Colcha "K" and Cochabamba (Valle Grande). *Planned (1021 kW)* in the states of La Paz (Inquisivi, Ixiamas, Ichoca, La Paz, and Apolo), Chuquisaca (Incahuasi), and Cochabamba (Mizque)	Under Operation: 581 Planned: 1897 families	8M	VMEEA and the KfW (German Credit Agency for Reconstruction)
2013-2017	Implementation of Rural electrification projects *(Implementación de Proyectos de Electrificación Rural-IPER)*	* Distribution grid extension (11 Projects)	States: La Paz (Municipalities of Santiago de Machaca, Caranavi, Batallas, Yaco, Licoma and Catacora) and Cochabamba	4000	5.4M	Local government of La Paz and VMEEA
2011-2017	Rural Electrification Program- *(Programa de Electificación Rural- PER)*	*Grid extension *Pilot project based on renewable energy (1800 solar PV systems)	*Grid extension:* States of La Paz, Cochabamba, and Oruro *Solar PV systems:* States of Pando (El Sena and Villa Nueva) and La Paz (Ingavi)	25000	60 M	Inter-American Development Bank (Credit Loan)
2011-2018	Rural Electrification with Renewable Energy *(Programa de Electificación Rural con Energía Renovable-PERER)*	*Implementation of hybrid systems (Diesel and solar, wind or micro-hydro generation) *Installation of Pico solar PV systems *Community Solar PV Systems (85 kW) and 500 Thermo solar systems in 350 rural schools, 50 hospitals, and 500 government buildings *3000 Solar lighting systems (LEDs)	States: Beni, La Paz, Potosí, Oruro and Santa Cruz	5000	NDF: 5.3M IDB: 0.020M	The Nordic Development Fund (NDF) and the Inter-American Development bank (IDB) and the GoB

4.1.2. Lessons derived from the Bolivian electrification policy

Achieving universal access by 2025 represents a major challenge for the GoB. Overall, Bolivia aspires to be able to "export energy and position the country as South America's energy hub, supporting scientific and technological sovereignty" (Lokey, 2012, p.10). Within this process, the country has implemented different electrification initiatives, such as the PEVD, not only to enable access to electricity for all but to facilitate and promote productive and social uses of the installed infrastructure.

Based on the national plan for the electricity sector 2015-2025 and the projections of the national statistics institution, Bolivia was on track to achieve universal access in urban areas, by 2020. So far, as of 2016, urban areas already achieved a 99% of electricity coverage, through the densification of the distribution grid. But, in rural areas, as of 2016, 27% of the rural population still lacked access to electricity, and therefore, full coverage is only projected to be attained by 2025 (VMEEA, 2008a). This suggests that disparities in electricity access still exist between urban and rural areas. Although electricity access rates more than doubled between 2005 and 2016 (See Figure 4.3), universal access will require not only continuing with current electrification programs but also maintaining the government's strong commitment to the monitoring of the projects.

Table 4.2 presents the main institutional, technical, economic, social, and environmental lessons derived from the implementation of rural electrification initiatives in Bolivia. These aspects could be considered successful factors in the rural electrification efforts to achieve universal access in Bolivia. Thus, the Bolivian experience can contribute as an example for countries in Sub-Saharan Africa, Asia, and Latin America, with similar natural and socio-economic conditions, where electricity coverage continues to be low despite many decades of electrification efforts (Banal-estañol et al., 2017b).

Table 4.2 Lessons from rural electrification programs implemented in Bolivia. Source:(CEPAL, 2012; INE, 2016; OPHI, 2018; Parra-peña et al., 2013; UNDESA, 2013)

Lesson	Description	Source
Institutional	• Effective cooperation between private and public institutions creates confidence in the community. It guarantees the successful implementation of rural electrification projects, especially the dissemination of energy systems. • Monitoring, regardless of the source of financing, is essential to track the progress of rural projects and promotes quality control through standardization of procedures, tenders, routines, and planning. For instance, in Bolivia, the IDTR (Decentralized Infrastructure for Rural Transformation) project, financed by the World Bank, created a monitoring and evaluating office to perform frequent and periodical visits to the project and its beneficiaries, to communicate with solar home systems service providers, and to coordinate with distribution companies.	(Smart Villages Initiative, 2016; World Bank, 2011)
Economic	• Rural electrification decreases household expenditures on low-efficiency energy sources such as kerosene lamps, candles, and batteries. For instance, in Bolivia (as of 2013), expenditures on energy sources corresponded to about 78% of the total family's expenditures, and the use of kerosene lamps, candles, and batteries was still the main energy source. • Access to electricity enables business opportunities and local entrepreneurship because people seize the productive use of electricity by relying on more advanced machinery while delivering better quality products. • Electricity alone is insufficient to stimulate production. In some cases, there is little opportunity to use modern energy to expand services and products, as the market for luxury goods or services is limited and the market for basic goods is stable.	(Canedo Espinoza, 2005; UNDESA, 2013; van Dijk and Clancy, 2010)
Technical	• Systems scalability: It is essential to account for future demand growth to avoid oversizing the energy systems. • Commitment to allocate technical staff to check for maintenance (e.g. carried out every 6 months) guarantees the projects' sustainability. • Rural electrification initiatives need to account for geographic constraints. Access to remote rural communities is particularly challenging and expensive: the report presented by the World Bank for the IDTR project showed that frequent floods and landslides (a consequence of the difficult mountainous terrain of the high plateau and valley zones) increased the infrastructure and operational costs of the project. • Check for local conditions and access to services, such as clean water. According to the company Sico Solar, when installing solar water heaters in rural communities of Bolivia, they had to modify the system design due to the lack of clean water for systems with antifreeze. As a result, the material was changed to stainless steel to avoid problems caused by the use of poor-quality water. • Building local capacity in the communities is a strategy to create long-term engagement and familiarize the user with the correct use and primary maintenance of the equipment. Trained people could provide maintenance for the equipment to prevent breakdowns or to fix a damaged PV solar system. Developing publications such as information brochures, user manuals, or technical procedures could support this training. • Community ownership: Results of the rural electrification project implemented by Soluciones Prácticas resulted in the creation of a community electricity utility, which is managed by the community itself. They provide maintenance and inspection of the system, and the service provider is only responsible for monitoring longer-term operation and maintenance.	(Parra-peña et al., 2013, p-15; UNDESA, 2013; United Nations Developmen t Programme (UNDP), 2018a)
Social	• Access to electricity strengthens social interactions among community members because business hours are extended, and social activities can be held. • Street lighting has reduced insecurity on the streets. • Health improvements: Hospitals with access to electricity can stay open longer and provide cold chains for vaccines. • Enabling access to television/radio has improved health education dissemination and has increased communities' knowledge about political events. • Migration between rural and urban areas has reversed. For instance, after installing a 60 kW micro-hydropower system in the Municipality of Guanay, people returned to their community, given the availability of job opportunities in four production units of crafts and fabrics.	(Smart Villages Initiative, 2016; van Dijk and Clancy, 2010)
Environmental	• Switching from smoky candles and other fuel-based lighting sources (e.g. kerosene) to electric light has improved indoor air quality. • Switching to electric machines is less polluting because these appliances have lower noise levels, dust, and smoke which favours a healthier and less stressful working environment. • Using electricity for radios has reduced the need for batteries. However, soil and water pollution from battery disposal continues albeit at a reduced level. Results from a field study in communities of Cochabamba state show that 20% of households were still using batteries.	(Smart Villages Initiative, 2016; van Dijk and Clancy, 2010)

4.2. Peru

4.2.1. Peru's National Rural Electrification Policy

The energy system in Peru is divided into the National Interconnected Electrical System (SEIN, its acronym in Spanish) and the isolated systems (SA, its acronym in Spanish), from which Rural Electrical Systems (SER) are developed. The SEIN has a total installed capacity of 15340.3 MW (as of 2021) and it serves the country's 24 states, except for the state of Loreto, as presented in Figure 4.4. Its energy matrix is dominated by thermal generation (57%), followed by hydropower generation (37%) and renewable energy generation (about 5%, i.e. wind, solar, biomass, and small hydro) (OSINERGMIN, 2021).

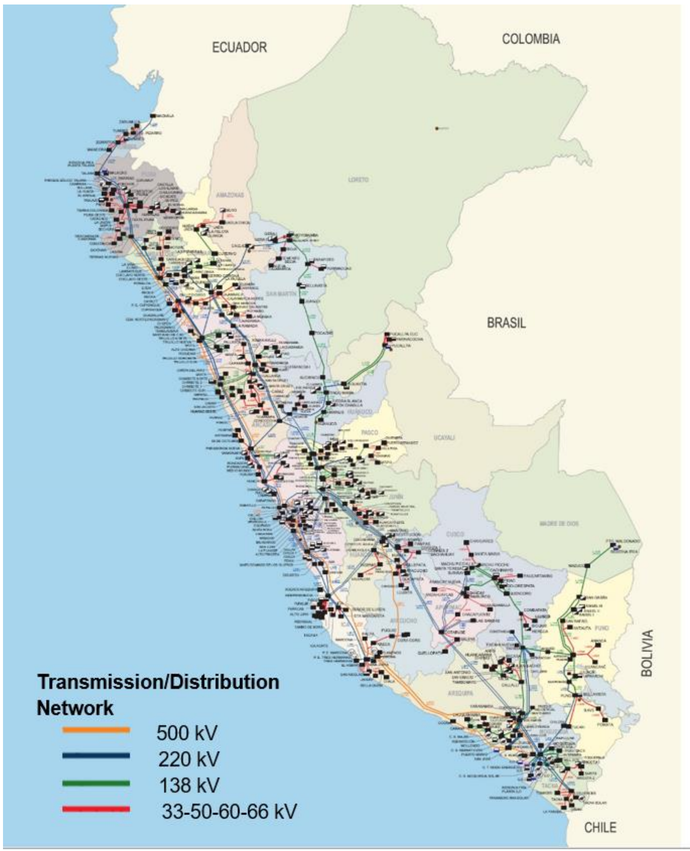


Figure 4.4 National Interconnected System of Peru (2021). Source: The National Interconnected System Financial Operation Committee (COES) (COES, 2021)

The Ministry of Energy and Mines (MINEM), through its attached unit, the General Directorate of Rural Electrification (DGER), is responsible for promoting the expansion of the coverage of electricity service in rural, remote, and border communities of the country.

Rural electrification in Peru is governed by Law No. 28749 of 2006 "General Law of Rural Electrification", which establishes the normative framework to promote the development and deployment of rural electrification in the country. The Ministry of Energy and Mines (MEM), through its attached unit, the General Directorate of Rural Electrification (DGER), is responsible for promoting the expansion of the coverage of electricity service in rural areas, and isolated and border towns of the country.

During the last decades, the Government of Peru (GdP) has promoted rural electrification in the country, through the implementation of extension projects of the SEIN and the SA, from which Rural Electrical Systems (SER) are developed. As a result, according to the National Rural

Electrification Plan (PNER) 2021-2023, Peru's electrification rate increased from 74.1% in 2007 to 87.9% in 2017 (MEM, 2020).

Despite this increase, as of 2017, there were still disparities between rural and urban electrification rates, which corresponded to 93.6% and 65.3%, respectively (MEM, 2020). According to the Latin American Energy Organization (OLADE), as of December 2020, there were about 350,000 households in Peru that did not have access to electricity (OLADE, 2022). These figures indicate that a major national boost to rural electrification is needed to reach a rural electrification rate of 100% by 2030, in compliance with the SDG7 of the United Nations. Some of the key challenges are related to techno-economic constraints to extending the grid to remote and rural areas, mainly due to the following factors: topographic conditions, dispersed communities, low energy demand, and lack of payment capacity (Lucas et al., 2020).

Table 4.3 provides an overview of different rural electrification initiatives in Peru, which are worth mentioning. Some of the key lessons derived from the implementation of these rural electrification programs include: (i) The definition of a single tariff for solar home systems (SHS) at the national level, independent of the area or the investment of the government is required; (ii) the georeferenced user identification requires a large part of the capital investment; (iii) an integrated energy planning with different electrification modes is essential; (iv) the active involvement of local communities has a positive impact and translates into a high level of collection, service acceptance, and user appropriateness; (v) there were difficulties in establishing the minimum volume of users to be auctioned, in order to attract more investors by promoting economies of scale; (vi) the technical requirements of the auction were very specific and reduced the possibility of submitting proposals with more efficient/optimal systems for the same level of service (i.e. including the integration of prepaid technology) and (vii) users need to be informed about the cancellation of service policy in case of no (or late) payment after 2 to 6 months (Eras-Almeida et al., 2019; Feron and Cordero, 2018; Lucas et al., 2020; Orozco, 2016).

The case of Peru is relevant for the scope of this thesis because the Country's public policy has promoted the implementation of renewable energy technologies, specifically individual solar PV systems, as a first alternative to extending the grid to rural and remote areas. Both individual and community systems have been installed in households, schools, and public buildings, respectively (MEM, 2015). In 2014, the GoP implemented the first off-grid auction to award a 15-year concession to provide electricity in three off-grid zones of the country, through SHS, in three zones of the country. The main goal was to attend a minimum of 149,000 households (~50,000 per area), 630 health institutions, and 2260 schools (Lucas et al., 2020). However, the operational results of the auction show a high risk for the sustainability of the project, since nearly 90% of users do not pay their monthly fee. Also, by July 2019, there were about 133,800 SHS already installed, which was still below the 149,000 minimum required for August 2016.

Overall, Peru's solar PV off-grid electrification auctions with their associated design elements (i.e. volume of the auction and product auctioned, bidding process, among others) could be used as a reference for other South American countries looking to scale up renewable energy systems.

Table 4.3 Overview of rural electrification initiatives in Peru (2005-2030). Source: Author's compilation based on (Feron, 2018), (PNER 2016), (OMIN, 2017), (Eurosolar, 2013) (JICA, 2008)

Period	Project	Features	Location	No. of beneficiaries	Investment ($ US)	Source of financing
2008-2020	Plan Maestro de electrificación rural con Energía Renovable	Micro hydropower generation (519 localities) Solar PV (10,829 localities)	Throughout the country (24 departments)	Microhydro: 18,498 households Solar energy: 261,520 households	217.5 M	SPERAR Fund (DGER/MEM)
2007-2011 2011-2013	EURO-SOLAR Program	130 Hybrid systems (Solar: 1000 Wp and Wind: 400 W)	Amazonas (15), Cajamarca (16), Lamayeque (3), Piura (16), Ayacucho (9), Huancavelica (7), Ica (19), Junin (10), Puno (34), Tacna (1)	130 schools	8.6 M 1.7 M	EU and DGER/MEM
2006-2011	Rural Electrification Improvement Project I (FONER I)	Grid Extension PV systems: 7,100 SHS	Piura, Ancash, , Cajamarca, Puno, San Martín, Ucayali, Madre de Dios, Apurimac, La Libertad, Pasco, Junin, Huanuco Huancavelica	105,000 households and small business (Including 2,900, schools, health clinics, and community centers)	129.5 M	International Bank for Reconstruction and Development (IBRD) (Loan) –World Bank, GEF, Direction of Grant Funds (DFC)/DGER/MEM and Local Companies
2011-Under operation	Rural Electrification Improvement Project I (FONER II)	Stage I: 19 Projects Stage II: 12 Projects Goals: 42,000 new connections (timeframe 20 years) 34,000 new connections (including the installation of 11,000 SHS) 5000 Units for Productive Use	Lima, Ayacucho, Arequipa, Cajamarca, Puno, San Martín, Amazonas, La Libertad, Pasco, Junin, Huanuco, Huancavelica, Iquitos, Ancash	142,000 (expected)	82.7 M	International Bank for Reconstruction and Development (IBRD) (Loan) –World Bank, GEF, Direction of Grant Funds (DFC)/DGER/MEM and Local Companies
Endev1: 2005-2009 Endev2: 2009-2018	Endev Project	Households and Social institutions: PicoPV systems, improved cookstoves, and grid connections Smallholder farmers: Grid connections and equipment for productive uses in the agricultural sector	Ucayali, Pasco, Lima, Huancavelica, Loreto, Madre de Dios, Puno, Tacna, Moquegua, Arequipa, Ayacucho, Ica, Apurimac, Cuzco, Junin, Ancash, Lambayeque, San Martin, Tumbes, Piura, Amazonas, Cajamarca, La Libertad	Achieved until 2017: Around 544,000 people 2,900 social institutions have electricity and/or cooking/thermal energy. About 14,300 small and medium enterprises (SMEs) have gained access to modern energy services.	17 M	Implemented by GIZ, Inter-American Institute for Cooperation on Agriculture (IICA), PracticalAction, MFI Caja Arequipa and financed by the Netherlands, Germany, Australia, Great Britain, Norway, and Switzerland.
2015-2030	Energy Auction (commissioned by the MEM-2014) to promote rural electrification through solar PV systems "Massive Program"	1st stage: 150,000 and 2nd stage: 500,000 stand-alone PV systems	Three zones: North, central and Southern region	50, 000/ per year (for 15 years)	8 M/ per year (for 15 years)	OSINERGMIN/MEM: Tender bid winner (Ergon)

5.Identifying key challenges for off-grid electrification in rural areas: the case of Colombia

This chapter provides an overview of the national rural electrification policies in Colombia, identifying the key hurdles or challenges hindering the progress towards providing electricity service to the last-mile communities of the country. Following discussions with multiple stakeholders and experts involved in the off-grid sector, this study identified a set of challenges grouped in four dimensions, namely financial/economic, social/cultural, technical, and policy/regulatory. These insights are crucial within the definition of sustainable rural electrification programs and policy guidelines because they provide a better understanding of the regulatory, financial, economic, social, and technical needs to guarantee the long-term sustainability of off-grid projects. Some of these challenges are not particular to the Colombian case, so they pose importance to other developing countries with similar geography, climate, development conditions, and facing energy access deficits.

5.1. Colombia

The Government of Colombia (GoC) has the ambitious goal of achieving universal access by 2030, this implies increasing the current electrification rate from 96.45% to 100%, according to the most recent indicative national plan for expanding electricity access (PIEC 2019-2023 in Spanish). Unfortunately, deficits in access to electricity still prevail in rural areas, where the electrification rate corresponds to about 86.54%, compared to urban areas where 99.51% of the people have electricity access (UPME, 2019a). Estimations of the electricity access index (ICEE in Spanish) indicate that 9 out of the 33 states have total indexes below 90% and rural indexes below 65%, as presented in Figure 5.3 b (UPME, 2019b).

5.1.1. Colombia's electricity rural electrification policy

Colombia's national electricity system is divided into the National Interconnected System (SIN in Spanish) and the off-grid system, also known as the Not Interconnected Zones (ZNI in Spanish) (See Figure 5.3). As of January 2022, the total installed generation capacity in the SIN was 17,762.19 MW, from which 67.24% corresponded to hydropower plants, 30.79% to thermal plants (i.e. Natural Gas, liquid fuels, and coal), and about 1.95% with Non-Conventional Renewable Energy resources (i.e. wind, solar, and biomass) (XM, 2020).

The Colombian off-grid system spans over 53% of the national territory and corresponds to a set of geographical areas where the public electricity service is not provided through the SIN, according to Law 855 of 2003. It comprises more than 1797 localities (as of November 2021) grouped in 76 municipalities within the country (See Figure 5.1). In these areas, the total installed capacity is about 299.43 MW, relying mainly on diesel-powered plants (88%) in contrast to 12% or 34.53 MW that depends on non-conventional renewable energy, as presented in (See Figure 5.3 a). (IPSE, 2022).

Figure 5.1 also shows the distribution of the 1797 localities that conform to the ZNI. They are divided into four categories: 1) Type 1: Localities with more than 300 users; 2) Type 2: Localities with 151 to 300 users; 3) Type 3: Localities with 51 to 150 users; and 4) Type 4: Localities with 1 to 50 users (MME, 2007). Currently, 86.1% of the localities correspond to Type 3 and 4, where 42.7% of the ZNI families are concentrated. On the other hand, 13.9% of localities (Type 1 and Type 2) concentrate

57.3% of the users, which shows the dispersion and challenges in terms of economies of scale for the electricity service provision in these areas (CNM-IPSE, 2021).

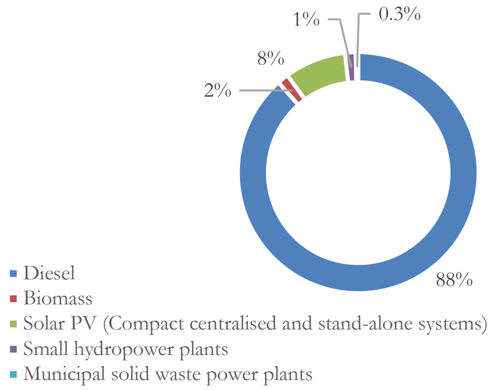


Figure 5.1 Installed capacity (%) by the technology in the ZNI. Source: (IPSE, 2022)

Overall, these off-grid areas exhibit particular socio-economic characteristics: high index of rurality (79% corresponds to rural population); highest deficits in access to electricity (~70% of the households living without electricity are located in the ZNI); lack of a reliable electricity service (where available); highly dispersed population (~3 inhabitants/km²); low levels of payment capacity; high difficulties in payments collection; topographic complexity (i.e. communities located in jungles, deserts or mountains); areas vulnerable to the country's internal conflict, and nearly 77% of people have unsatisfied basic needs (UBN) (CNM, 2018; IDB, 2016; IPSE, 2020b; UPME, 2019b).

There are six main stakeholders involved in the electricity supply chain in the ZNI, as illustrated in Figure 5.2.

The MME manages the electricity sector in Colombia, including the off-grid zones. It is responsible for the "policy formulation, the definition, and application of subsidies, and overall coordination of government entities and their relationship with public utilities and private companies" (IDB, 2016). The MME has the technical support of the Planning Unit on Mining and Energy (UPME), which formulates the national generation and transmission plans, and the indicative planning to achieve universal electricity access for interconnected and off-grid areas by 2030. This entity assesses the opportunities and investment needs to expand energy access, mainly from renewable energy (RE) technologies in the ZNI. The Institute for the Planning and Promotion of Energy Solutions in the ZNI (IPSE) identifies, promotes, structures, implements, and monitors sustainable energy solutions in the ZNI. It also provides support in the evaluation of off-grid electrification projects proposed by external entities and works closely with public service providers in the ZNI. The Regulatory Commission for Energy and Gas (CREG) regulates the public services of electricity, fuel gas, and liquid fuels. It is the sole body responsible for the definition of technical regulations and tariff schemes applicable to the SIN and the ZNI. Under the label "Surveillance and Control", there is the SSPD, a technical organism in charge of protecting the rights of domiciliary services users by inspecting and controlling the entities and companies that provide residential public services (i.e. water, sewage, sanitation, energy, and gas). Table 5.1 provides a summary of the main competencies of these institutions and their role in the off-grid energy sector of Colombia.

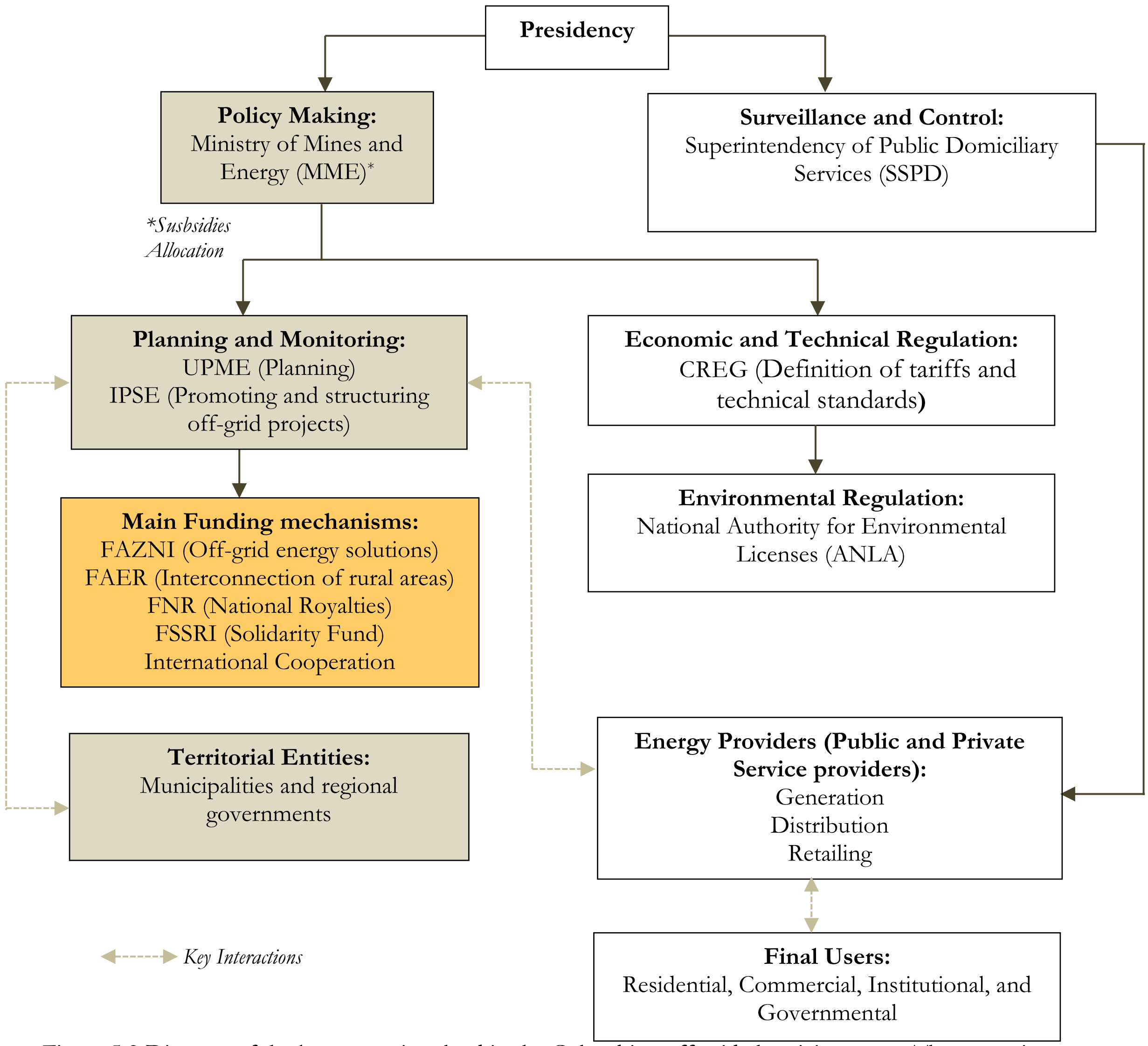
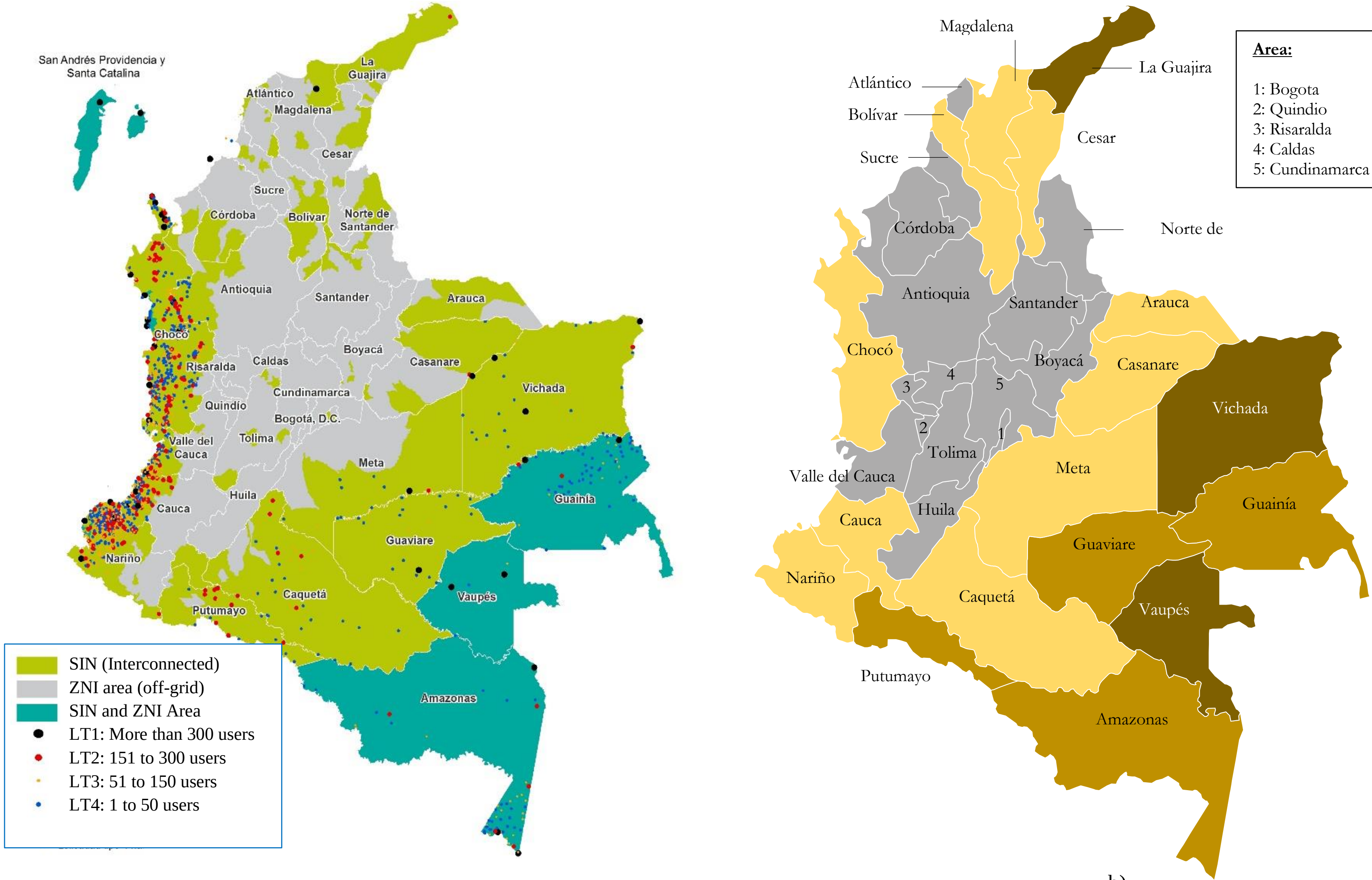


Figure 5.2 Diagram of the key actors involved in the Colombian off-grid electricity sector. The actors in grey-coloured boxes correspond to those that are directly involved in resource allocation and/or policy making. Source: Adapted from (Rodriguez, 2017)

Table 5.1 Main competences of the institutions involved in the off-grid sector of Colombia. Source: Author's own

	Competences								
Institutions (Stakeholders)	**Policy definiti**	**Financi ng**	**Subsidi es**	**Regula tion**	**Energy Planni**	**Project s**	**Project s**	**Project s**	**Monito ring**
MME	x	x	x						
CREG				x					
UPME					x				
IPSE		x				x	x	x	x
SSPD									x
Grid Operators, Local authorities (Mayors or territorial entities)						x		x	
International Donors/Cooperation		x					x	x	



b)

Figure 5.3 a) Location of the non-interconnected zones (ZNI) or off-grid areas in Colombia (2021) and b) National electricity access index Source: Adapted from (IPSE, 2021a; UPME, 2019b)

Regarding the legal and regulatory framework applicable to the rural electrification sector, the Colombian State Constitution of 1991 and Laws 142 and 143 of 1994 declare that access to electricity is a civil right that should be guaranteed by the state. In addition, there are a set of resolutions and decrees that set the regulatory and policy directives to regulate and promote the energy provision within the ZNI. They are mainly focused on defining a set of policies to promote electricity access, the definition of the tariff scheme, the subsidies regime, and the role of different stakeholders. Table 5.2 presents a partial depiction of the current legislative framework.

Table 5.2 Excerpt of the main policy, regulatory and legal framework associated with the off-grid electrification sector in Colombia. Source: Author's own from current legislation

National Policy	• CONPES Document 3108 of 2001- "Energy Program for the off-grid areas (ZNI)" • CONPES Document 3055 of 1999- "Strategies and actions for the Energization of off-grid areas (ZNI)" • CONPES Document 3453 of 2006- "Management Schemes for the energy service provision in off-grid areas (ZNI)" • Documento CONPES 3453 de 2006 - "Esquemas de Gestión para la Prestación del Servicio de Energía en las Zonas No Interconectadas" • Document CONPES 3587 of 2009- "Concession of exclusive service areas declared as projects of strategic importance for the country." • Decree 1073 of 2015, 1623 of 2015, 1513 of 2016, and 099 of 2021- Main Decree of the Mining and Energy Sector policy and amendments associated with the policy guidelines for the expansion of the electricity service coverage in the national interconnected system (SIN) and the off-grid areas (ZNI). • Decree 847 of 2001 and 201 of 2004-FSSRI regulation • Decree 1124 of 2008: FAZNI regulation
Laws	• National Constitution of 1991- Access to electricity as a civil right • Law 142 of 1994- Public Services Law • Law 143 of 1994- Electricity Sector Law • Law 855 of 2003- Definition of off-grid areas (ZNI) • Law 633 of 2000- FAZNI creation • Law 788 of 2002- FAER creation • Law 286 of 1996- FSSRI creation • Law 1715 of 2014-FENOGE creation • Law 413 of 2018- SGR resources for rural electrification • Law 1955 of 2019-National Development Plan 2018-2022 • Law 2099 of 2021-FONENERGIA creation
Planning	• Indicative Plan for the Electricity Coverage Expansion (PIEC) 2019-2023 • Sustainable Rural Energy Plans (PERS) • National Rural Electrification Plan (PNER) 2018-2031 • Development Programs with a Territorial Approach (PDET) • "We are all Pazcífico" Plan (PTSP)
Regulations	• CREG resolution 091 of 2007- Tariff scheme for the electricity service in off-grid areas (including exclusive service areas) based on Diesel generation, small hydropower plants, hybrid minigrids, and stand-alone systems (≤500Wp) • CREG resolution 166 of 2020- Transitory Tariff scheme for the electricity service in off-grid areas based on stand-alone systems (>500Wp) • CREG resolution 701 001 of 2022 (pending approval)- Tariff scheme for the electricity service in off-grid areas based on stand-alone systems (>500Wp) • MME resolution 182138 of 2007- Subsidies definition for the off-grid areas • UPME resolution 045 of 2016- Non-conventional energy resources (FNCE) incentives

5.1.2. Funding mechanisms associated with electrification projects in the off-grid areas

Historically, the electricity service in the ZNI has relied on a subsidised business model, in which the GoC provides financial support to the Capital Expenditures (CAPEX) and the Operating Expenses (OPEX) of the off-grid electrification projects. In the former case, project developers receive a 100% subsidy on the CAPEX required for the installation of the infrastructure. These resources come from different public funding mechanisms, depending on the type of financial support they offer, as presented in Figure 5.4.

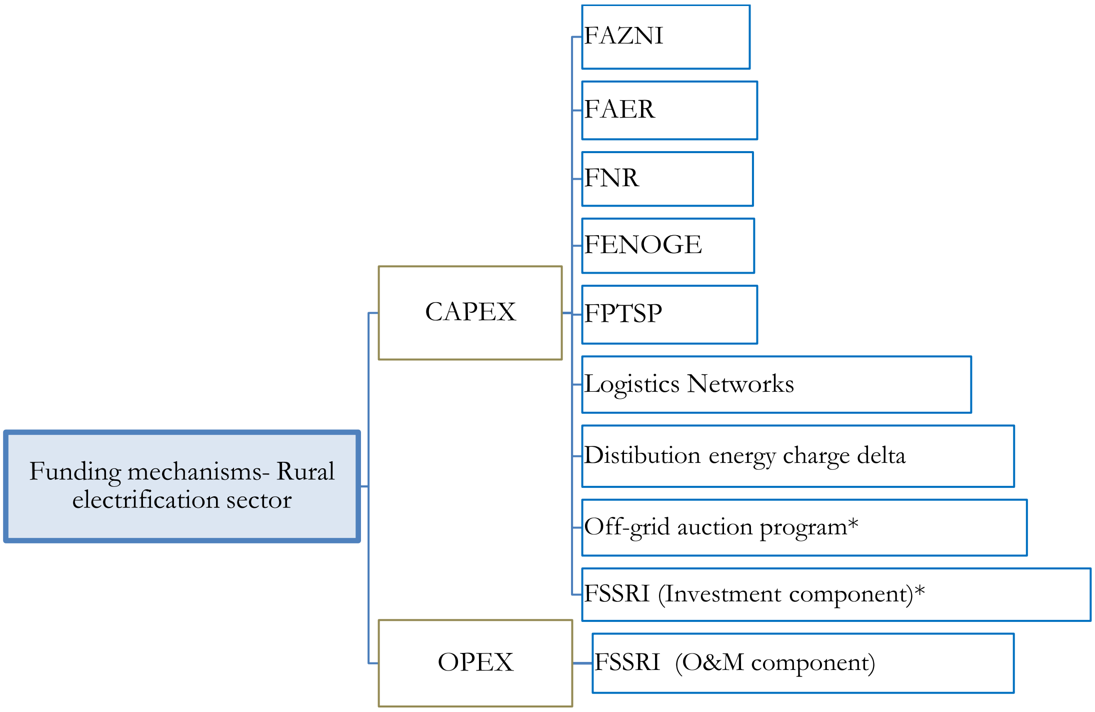


Figure 5.4 Overview of the main funding mechanisms financing rural electrification projects' CAPEX and/or OPEX; (*) corresponds to those mechanisms being designed. Source: Author's own from the current regulatory framework

The financial support fund for the electrification of non-interconnected areas (FAZNI), the fund for the electrification of interconnected rural areas (FAER), the National Royalties Fund (FNR), the non-conventional energy resources and Energy Efficiency Fund (FENOGE), and the Fund for the development of the Plan "We are all Pazcifico"(FTSP) (MME, 2021a) correspond to public financial funds financing the CAPEX of rural electrification projects. Table 5.3 presents a brief review of these funds.

Most recently, in 2021, the MME also set two additional mechanisms to fund rural electrification projects. Through the Decree 099 of 2021, the MME modified Decree 1073 of 2015 (The main regulatory decree of the MME) to adjust the policy guideline for the electricity coverage service expansion in the SIN and the ZNI. As a result, the FAZNI resources can be used to finance projects and plans to expand electricity access to remote communities, through physical networks or logistics networks in rural and interconnected (i.e. influence areas of the grid operators). Also, it published a project resolution to regulate art. 2.2.3.3.1.9. of Decree 1073 of 2015 to set the maximum tariff increase to remunerate grid operators investing in electricity expansion projects and the prioritization criteria to be applied by the CREG to include this "delta" in the respective distribution energy charge of the electricity bill.

Currently, the MME with support from IPSE is working on designing a competitive mechanism to grant a long-term contract through an auction program to a private company willing to invest in off-grid electrification projects of the ZNI in specific areas of responsibility. In return, the GoC provides a set of public incentives to guarantee the project's financials and a sustainable business model for the selected energy service provider(s). In addition, the MME is also working on evaluating the alternative of providing capital investment to off-grid electrification projects with resources from the solidarity fund or FSSRI.

Table 5.3 Financing funds promoting rural electrification in off-grid areas. Sources: Author's own from (MME, 2021a)

Year	Definition	Objective	Average available annual resources* (2016-2020)
1991	National Royalties Fund *(Fondo Nacional de Regalías, FNR-OCAD)*	It corresponds to a national fund that collects the income from royalties that are not directly allocated to the departments and municipalities. Since 2011, this fund can finance or co-finance electricity expansion projects in the ZNI, granted by the decision-making collegiate body (OCAD in Spanish).	~ € 12 million (specific to rural electrification activities)
2000	Financial Support Fund for the Electrification of Non-interconnected Areas *(Fondo de apoyo financiero para la energización de las zonas no interconectadas, FAZNI).* Law 633 of 2000 (art. 82)	Finance of plans, programs, and investment projects in energy infrastructure aimed at expanding electricity coverage in the ZNI, under the law and the energy policies determined by the MME.	~ € 25 million
2002	Fund for the Electrification of Interconnected Rural Areas *(Fondo de Apoyo Financiero para la Energización de las Zonas Rurales Interconectadas, FAER)*	It provides financial support to plans, projects, and programs seeking to expand electricity coverage in interconnected rural areas, through the construction and installation of new electrical infrastructure, following the coverage expansion plans by each of the distribution system operators (DSO)	~ € 33 million
2014	Non-Conventional Energy sources and Energy Efficiency Fund *(Fondo de Energías No Convencionales y Gestión Eficiente de la Energía, FENOGE)*	It provides financing (partially or totally) to programs and projects aimed at implementing small-scale renewable energy generation systems and/or promoting energy efficiency in the residential sector (low-medium income users).	~ € 7-10 million
2015	Fund for the Development of the Todos Somos PAZcífico Plan (FTSP),	It was created to implement the Todos Somos PAZcífico Plan. It provides investments to finance electrification projects that promote development and better quality of life for the communities of the Pacific Region.	~ € 24 million
2021	Unique Fund for Energy Solutions (*(Fondo Único de Soluciones Energéticas, FONENERGÍA)*	Finance of plans, projects, and programs aimed at expanding and improving the provision of electricity service, through electrical energy and fuel gas solutions with criteria of environmental sustainability and social progress. This fund is under the regulatory definition, but it is expected to integrate FAZNI and FAER's resources.	TBD

* 1 EUR= COP $4,000

From this set of funds, the FAZNI is the main funding mechanism to finance off-grid projects in Colombia. It provides capital investment to cover equipment costs, engineering, construction, legal and contractor fees, and the households' electrical installations in the ZNI. Resources allocated to this fund come from the collection of COP$1.90/kWh dispatched in the spot energy market, of which COP$0.4/kWh is used to finance the FENOGE (art. 190 of Law 1753 of 2015). Between 2010 and 2020 the FAZNI financed most of the generating capacity in ZNI, allocating about US $300 million through 205 projects and benefiting more than 1 million people (MME, 2020a). These electrification projects have been approved through two schemes: 1) As a result of public invitations designed by the MME, for infrastructure investment projects in non-interconnected areas, and 2) On the initiative of local authorities (e.g. local municipalities' mayors, departments, or ethnic communities that have the endorsement of the territorial entity), and the IPSE. Recently, the Law 2099 of 2021 created FONENERGIA, a fund that will replace the following existing funds: the Electrical Network Standardization Program (PRONE), FAER, FAZNI, and the Special Natural Gas Development Fund (FECFGN).

In addition to these mechanisms, the GoC has implemented different regulatory reforms to encourage private firms to scale up RE investments, including i) the definition of two exclusive service areas (ASE), under a concession model for twenty years, in the San Andres & Providencia, and Amazonas Departments. These concessionaires not only provide initial infrastructure investments, but also, they are expected to renew investments every five years (IDB, 2016); and (ii) fiscal incentives (i.e. income tax deduction, accelerated depreciation, value-added-tax (VAT) exemption, and import duty exemption) under Law 1715 of 2014, to promote private capital investment in RE.

Regarding the OPEX, the GoC covers a percentage of these costs with the regulated tariff and a monthly subsidy on the end-user electricity bill. In return, service providers acquire the compromise to respond to the operation and maintenance of the infrastructure, under a Build, Operate, Maintain, and Transfer (BOMT) contract of about 5 to 10 years (IDB, 2016). This subsidy comes from the Solidarity Fund for Subsidies and Income Redistribution (FSSRI) and it is designated to protect energy users in the SIN and the SIN from high electricity prices, by covering a percentage of the electricity tariff. This fund is raised from all the energy users of higher strata (strata 5 and 6) as a contribution fee and in the case of ZNI, the subsidy corresponds to the difference between the cost of energy services in the ZNI locality and the user's tariffs in the closest SIN locality (Rodriguez, 2017). Unfortunately, this fund experiences a deficit every year, and the MME is forced to use loans from the national treasure to cover it.

Also, the GoC has defined a set of plans, programs, and/or missions, as presented in Table 5.2. Among these initiatives are the Sustainable Rural Energization Plans (PERS) of the UPME, the Todos Somos PAZcifico Plan (FTSP), and the National Rural Electrification Plan 2018-2031 (PNER), defined by Decree 884 of 2017, and aligned with the Development Programs with Territorial Approach (PDET). Currently, under the National Development Plan (PND) 2018-2022, the sectoral objective is to expand the coverage of electricity supply with public resources to 100,000 new households (close to 500,000 people) by 2022 (MME, 2021b).

5.1.3. The role of decentralised off-grid systems

During the last decade, the GoC has set different policies to achieve this purpose. In 2014, the MME set a national policy (Art. 9 of Law 1715-2014) aimed at implementing a program that progressively substitutes diesel generation in the ZNI with more efficient energy systems. In addition, in 2015, during the United Nations Framework Convention on Climate Change (COP 21), the Colombian government ratified its commitment to the fight against climate change and set the compromise to reduce national greenhouse gas (GHG) by 20% by 2030. Then, in 2020, under the energy transition of the current government, this commitment was modified to reduce 51% of the national GHG by 2031 (Ministerio de Ambiente, 2020).

Within this context, off-grid RE-based systems are a promising alternative not only to diversifying the energy matrix of the ZNI, but also to reducing GHG emissions from the use of fossil fuels, lowering the electricity service costs, increasing energy efficiency, and improving the quality of the electricity provision in these areas (IPSE, 2022). Thus, during the last decade, the UPME has modified different aspects of the energy planning methodology applied to the off-grid areas of Colombia. Consequently, the national electricity expansion plans, or PIECs, have evolved towards a transition to promote decentralised energy systems with more efficient and cleaner energy technologies. Table 5.4 presents the main changes within the last four plans: PIEC 2010-2014, PIEC 2013-2017, PIEC 2016-2020, and PIEC 2019-2023.

Table 5.4 Methodological changes to the energy planning methodology in the off-grid areas of Colombia. Source: Author's own from (UPME, 2019a, 2016b)

Aspect	PIEC 2010-2014	PIEC 2013-2017	PIEC 2016-2020	PIEC 2019-2023
Electricity access rate (ICEE)	Urban and rural estimates per municipality of the SIN and the ZNI	Urban and rural estimates per municipality with the information provided by the grid operators, IPSE, and national census of 2005.	Urban and rural estimates per municipality and information provided by the PERS, surveys, and inclusion of photointerpretation for validation of spatial location in two Departments.	Urban and rural estimates per municipality were obtained from GIS information at the national level, PERS, reports from IPSE, and grid operators.
Total of households without electricity service (VSS)	562.074	470.244	425.215	495.799
Monthly electricity demand (kWh)		Grid extension: 92 kWh Diesel generation: Based on 33.6 and 76.8 kWh ((based on the MME Resolution 182138 of 2007)	All alternatives (24 hours of electricity provision): 92 kWh	For all possible alternatives, two possible solutions were considered: a) 90 kWh for altitudes below 1000 meters above sea level, and b) 60 kWh for altitudes above 1000 meters above sea level. In addition, for the alternative with micrograds, a simultaneity factor was also considered
Interconnection to the SIN	x	x	x	x
Alternatives comparison	Grid extension vs 24hrs of diesel generation	Grid extension vs 24hrs of diesel generation (based on the MME Resolution 182138 of 2007)	Grid extension vs hybrid microgrids: 1) Solar PV with battery storage 2) Solar PV with battery storage and diesel 3) Solar PV and wind with battery storage 4) Solar PV and wind with battery storage and diesel	Grid extension vs Stand-alone PV systems and hybrid microgrids (renewable energy based with annual diesel generation limited to 15%)

The most recent indicative plan was released by the UPME in 2019 (currently being updated) and it not only identifies the total number of households without electricity service but also the total public investment and type of energy solution required to provide electricity access to these families. Based on the Decree 1523 of 2015, the main objectives of the PIEC are: i) To identify the needs for the electricity service expansion, ii) To quantify the required investments to achieve universal access. Within this framework, the plan proposes three (3) technology options: extending the grid, namely through densification or intensification of the grid, implementing hybrid microgrids, and installing individual off-grid solar PV systems solutions.

The methodology proposes the best technological alternative to expanding the electricity service to 495,799 households that still lacked access to electricity by 2018 (UPME, 2019a). This selection depends on a series of social, technical, economic, and environmental parameters, including the level of electricity access, the density population, the distance to the national network, and the availability of local resources. These parameters are spatial, which makes geospatial information very useful for evaluation at regional and national levels. In consequence, the PIEC is based on a GIS model that evaluates the different technologies.

The methodology begins with the identification of the electricity service needs in each site[2] (See Figure 5.5) and the available electrical infrastructure from the NIS. Also, it identifies the energy source potential from the National Solar and Wind Atlas, released by the IDEAM in 2015 and 2016, respectively. For each Site, the interconnection alternative is initially evaluated depending on the proximity to the electrical infrastructure, namely the distribution grid. Then, for sites that are outside the area of influence of a MV and LV grid and if the group of households without service in each Site is greater than 25 households, the plan estimates the cost of implementing a microgrid. Finally, if the number of households without electricity is less than 25 users, the plan considers stand-alone systems as the best alternative.

After an individual evaluation for each site, the plan indicates the type of appropriate technology for each case. Based on these results, the plan quantifies the required investment to implement each alternative (UPME, 2019a). Figure 5.5 illustrates the PIEC 2019-2023 methodology, accounting for information provided by different institutions, namely the grid operators, the MME, the IPSE, and the IDEAM, among others. Considering the case of the five departments with the highest number of households without electricity access (as of 2018), namely La Guajira (81,960), Nariño (36,264), Cauca (32,275), Choco (29,558), and Valle del Cauca (27,782), this plan indicates that on average more than 70% of the households will gain electricity access through off-grid decentralised systems.

[2] A site could be defined as: i) a household located within a minimum flat distance of 400 meters from another household or to the centroid of a group of households, ii) a group of 2 or more households located to 400 m or less between them.

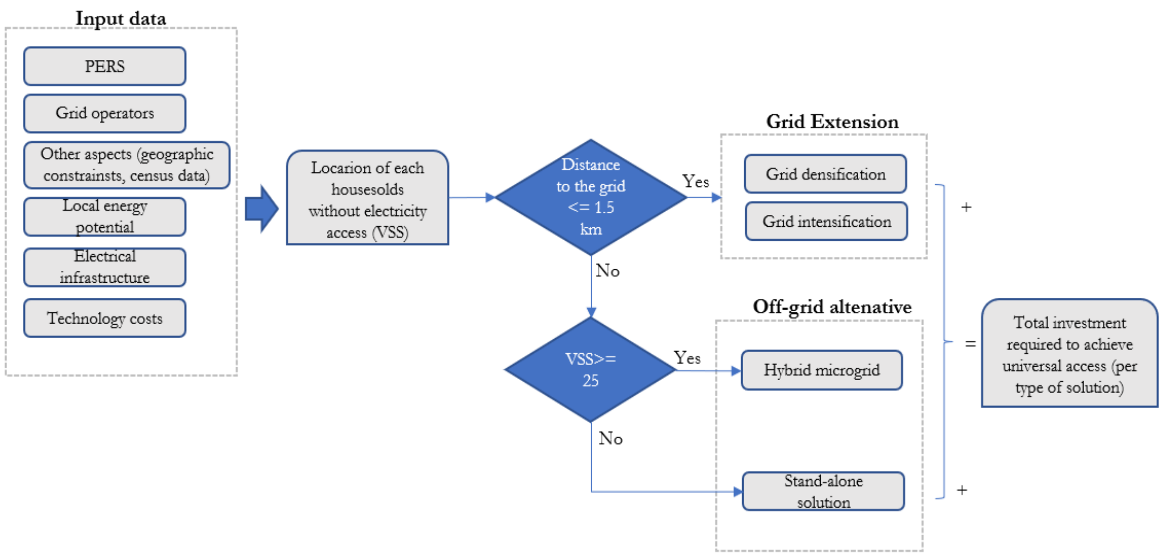


Figure 5.5 Methodology for selecting the best energy technology for electricity provision at the department and municipality level in Colombia. Source: Author's own from (UPME, 2019a).

5.1.4. Key lessons from the Colombian rural electrification policy

During the last decades, in the off-grid sector, national programs, plans, and projects have focused on achieving universal access by 2030, as it was set on the national policy "CONPES 3918 of 2018", in compliance with the commitment of the United Nations Sustainable Development Goal (SDG) 7. As a result of this effort, national electrification rates have increased from 76.1% in 1995 to 96.5%, in 2018, as presented in Figure 5.6 (UPME, 2019b). However, the largest deficit is still present in rural areas, where the electrification rate corresponds to 86.54%, compared to an electricity service coverage of about 99.51% in urban areas (UPME, 2019a, 2019b). There are still nearly 1.7 million people or 444,000 households lacking this service and for about 80% of them, the grid-extension approach is techno-economically unfeasible (IPSE, 2021b). Most of these un-electrified areas in Colombia are far away from the SIN and correspond to areas with less dense populations and lower demand. Thus, the situation of reaching this "last-mile" or remote rural areas will depend on off-grid energy technologies, namely stand-alone PV systems, and minigrids (UPME, 2019a), as presented in Figure 5.7.

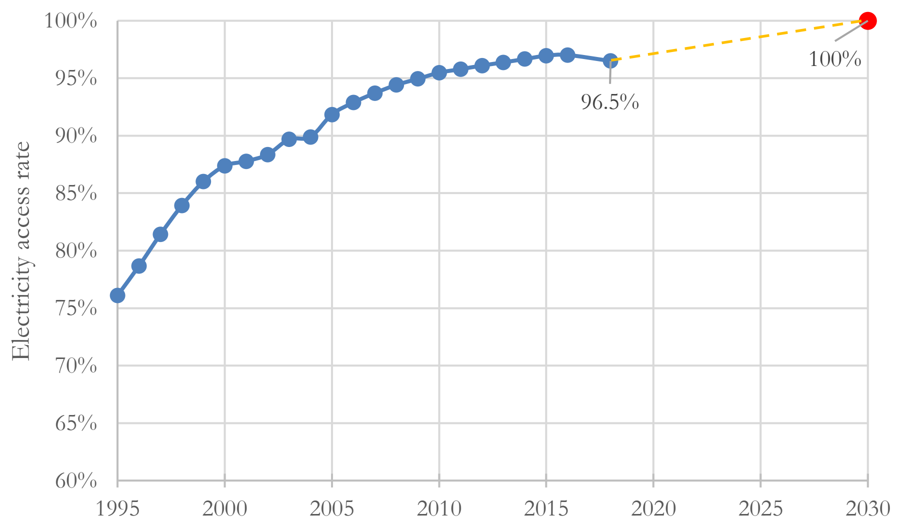


Figure 5.6 Progress in Colombia's electricity access rate between 1995 and 2018. Source: Authors' own from (UPME, 2019a, 2019b)

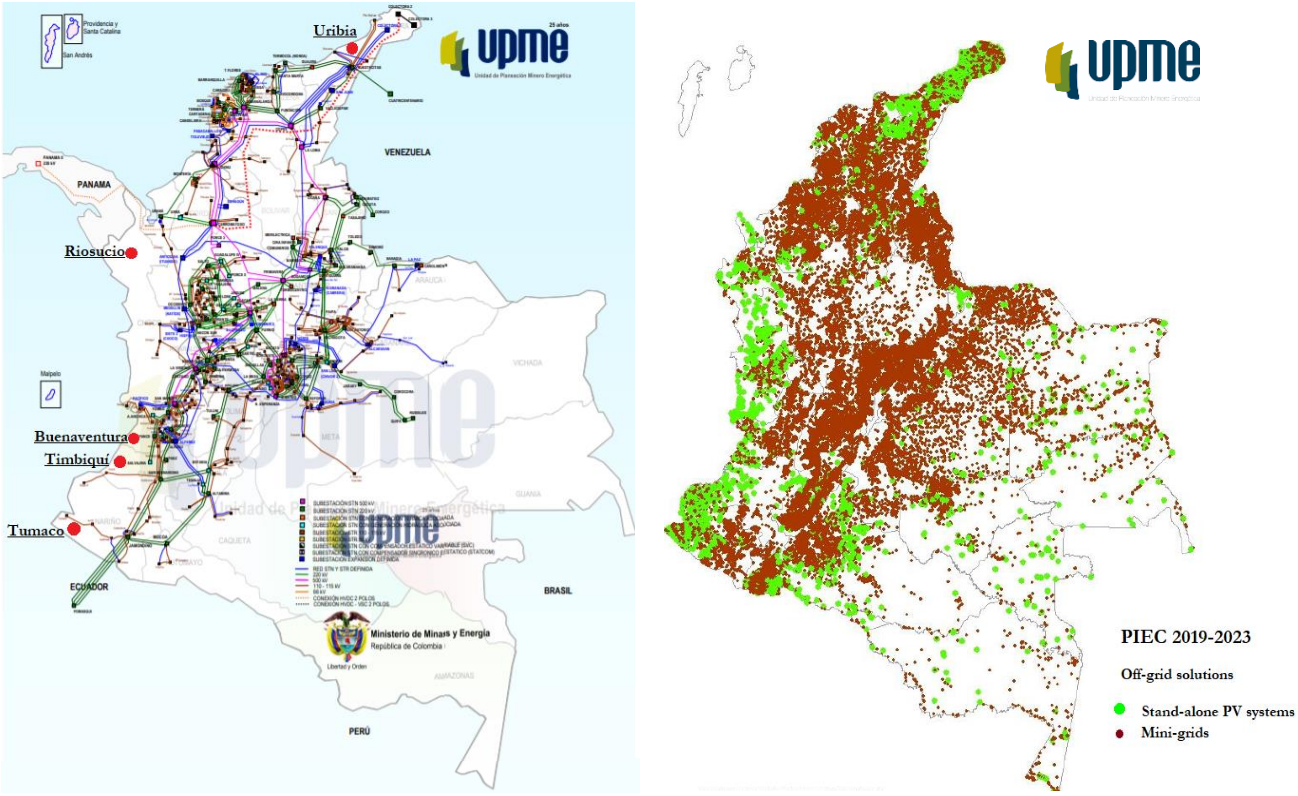
The implementation of different off-grid projects has provided a variety of lessons derived mainly from the perception of the community and the energy service providers operating in the ZNI. Unfortunately, there is a lack of national technical studies presenting the impact evaluation of these projects, mainly implemented with public funding. Table 5.5 summarises key lessons derived mainly from structured interviews collected in La Guajira, in 2020, and semi-structured interviews with off-grid energy service providers, in 2021. As part of this process, in 2020, I had the opportunity to run some surveys at five (5) Wayyuu families, within the following communities: Betania and Sinmana. I could only complete these surveys, because of the outbreak the COVID-19. Figure A1 (See Appendix Section) presents the survey format used to collect the information from local communities.

Table 5.5 Lessons from rural electrification programs implemented in Colombia. Source: Author's own

Lesson	Description
Institutional	• Support from National and County governments. A high degree of involvement of local governments guarantees a high degree of community ownership. • Impact evaluation. It is an essential component for identifying key lessons for future policies and investments.
Economic	• Projects require a sustainability scheme that considers users' ability to pay which differs from municipalities and depends on local socio-economic conditions. • Appropriate tariff design. Users' regular payments and subsidy allocation are critical to the provision of a sustainable service. • Income generation activities, e.g., micro-enterprise/micro-finance development, are an important aspect of developing a sustainable rural energy supply
Technical	• Engagement of energy service providers. Technical expertise/capability of local suppliers is critical to sustained operation, e.g., providing warranties and technical support or replacement.
Social	• Community participation throughout all the project phases is instrumental in engaging communities, creating awareness, and promoting regular payments and ownership of the projects. • There is not an official national report analysing how expanding energy access impacts socioeconomic development.
Environmental	• Reduction of noise pollution, reduction in exposure to combustion of solid fuels, reduction of fire risk and explosions.

According to the PIEC, prioritising the off-grid municipalities with the highest electricity access deficits (i.e. located mainly on the pacific coast of Colombia) (See Figure 5.7), namely Uribia (La Guajira), San Andres de Tumaco (Nariño), Buenaventura (Valle del Cauca), Riosucio (Choco), and Timbiquí (Cauca) requires a total up-front investment of €277 million to attend about new 60,000 households through off-grid solutions, mainly minigrids (~63.1%) (UPME, 2019a).

Unfortunately, policy measures have not been equally successful throughout the country and electrification rates differ among departments. Estimations of the electricity access index (ICEE in Spanish) indicate that 9 out of the 33 states have total indexes below 90% and rural indexes below 65%, as presented in Figure 5.3 b). La Guajira corresponds to the department with the highest deficit in electricity access. Overall, of the total number of households living without electricity service in the country (495,799 as of 2018), 81,960, or 17%, are within this region Figure 5.3 a). shows the total number of households without electricity services (VSS in Spanish) and the investment required by each department to achieve 100% electricity access. Departments with PDET municipalities, namely those territories most affected by violence, poverty, illicit economies, and institutional weakness (ART, 2022), are highlighted.



a) b)

Figure 5.7 a) Colombia's national interconnected system with planned expansion until 2034 (off-grid not included) and b) Off-grid solutions proposed by the PIEC 2019-2023. Source: Adapted from (UPME, 2021, 2019a)

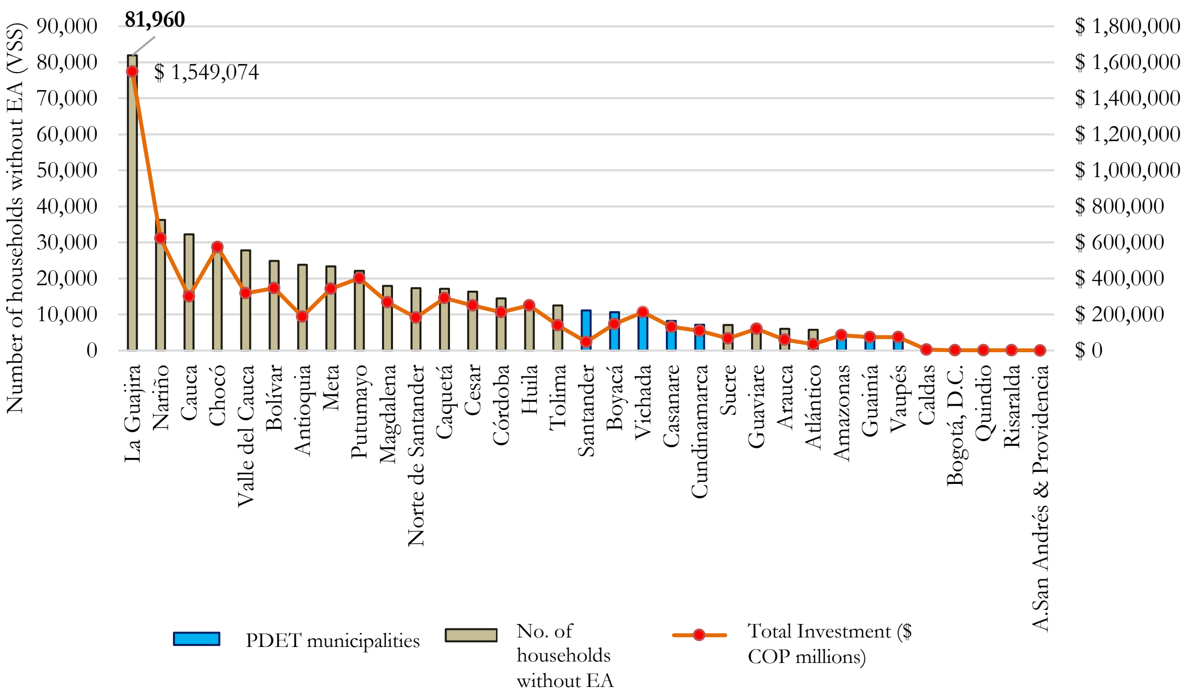


Figure 5.8 Colombia's electricity access index by department. Source: Autor's from (UPME, 2019b)

In line with this context, key challenges remain when it comes to providing electricity access to the last-mile rural communities. Some of these barriers have historically prevailed within the ZNI and have been identified in other public or academic studies (DNP, 2001, 1999; Gaona et al., 2015; Garces et al., 2021). This chapter identifies an overview of these hurdles hindering the progress towards achieving universal access, accounting for the perspectives of different stakeholders associated with the off-grid electrification sector in Colombia, namely off-grid service providers, public bodies, researchers, finance institutions, and grid operators.

5.1.5. Participatory process

This Chapter relies on information derived from semi a participatory process that resulted in eleven (11) semi-structured interviews with different stakeholders (i.e. directly related to the off-grid electrifications sector in Colombia, such as utility companies, off-grid energy service providers, academia, and the public sector (See Table 5.6). Guiding questions to open discussions with the participants were provided. These responses are presented as anonymous to respect participants' confidentiality.

Table 5.6 Participants involved in the semi-structured interviews.

Organization	Position/Area of specialization	Participants
Grid Operator 1 (GO1) *(Virtual meeting, 2021)*	Rural electrification, Social Worker	1
Grid Operator 2 (GO2) *(Personal communication, 2019)*	Energy planning division	1
Off-grid finance institution 1 (OFI) *(Personal communication, 2019)*	Business development	1
Off-grid energy service provider 1 (OEP1) *(Virtual meeting, 2021)*	Energy supply provider, project developer	1
Off-grid energy service provider 2 (OEP2) *(Virtual meeting, 2021)*	Energy supply provider, project developer	1
Off-grid energy service provider 3 (OEP3) *(Virtual meeting, 2021)*	Energy supply provider, project developer	1
Off-grid energy service provider 4 (OEP4) *(Personal communication, 2021)*	Energy supply provider, project developer	1
Off-grid energy service provider 5 (OEP5) *(Virtual meeting, 2021)*	Energy supply provider, project developer	1
Off-grid energy service provider 6 (OEP6) *(Virtual meeting, 2021)*	Energy supply provider, project developer	1
Academia (ACD) *(Personal communication, 2020)*	Researcher	1
Public Institutions (GOV) *(Personal communication and virtual meeting, 2021)*	Assistant Director, Advisor in Energy Planning	1

As part of the discussions, stakeholders focused on different challenges regarding the provision of electricity in off-grid areas of Colombia. They include a set of technical, social, policy/regulatory, and financial/economic aspects that have hindered progress toward the goal of universal access in Colombia, as presented in Table 5.7.

Financial and Economic challenges. During the last decades, the definition of public financing funds, changes in the regulatory framework focused on favouring the energy transition, and changes in the technology alternatives included in the PIEC, have facilitated the expansion and improvement of the electricity service in the ZNI. However, public resources are not enough to achieve universal access by 100% by 2030. This scarcity of capital is coupled with low participation of international cooperation financing and private investments in implementing off-grid RE-based projects of the ZNI (about 9.4%, as of 2016) (IDB, 2016).

Table 5.7 Off-grid electrification challenges by category. Source: Semi-structured interviews with 11 stakeholders

Category	Challenges	
Financial/ Economic	• High upfront investment costs. • Limited public resources (FAZNI, FENOGE, SGR, FPTSP, IPSE). • Limited private capital participation and financing resources from international cooperation • Investments in off-grid areas are considered high-risk by first-tier financial entities. • Projects with low return on investment than expected. • Uncertainty about customer churn rate. • Uncertainty about the projects' cost structure.	• Low payment capacity of users. • High O&M costs. • High cost of bank guarantees to support project proposals. • Higher levels of debt. • Uncertainty about the investment required to replace the systems' components. • Delays in the payment of subsidies.
Technical	• Demand uncertainty: Lack of reliable energy demand information. • Energy demand is lower than expected (low volume of users). • Local companies providing the service have deficiencies in their capacity to manage, operate and maintain the infrastructure. • Intermittency in the service provision, low coverage, reduced number of daily hours of service, and poor levels of quality and reliability of the service provided. • Lack of standardised technical level requirements. • Limited use of local RE potential.	• Lack of knowledge about the project area characteristics. • Lack of adequate remote monitoring systems. • Stranded infrastructure owned by the MME and IPSE. • Lack of effective revenue collection methods. • Lack of interest of network operators in dispersed markets.
Social/ Cultural	• Ability and willingness to pay. • The population density of the ZNI is extremely low (i.e. high dispersion of potential users). • Lack of local skilled personnel or local inappropriate infrastructure. • Community acceptance and involvement in the planning of the projects.	• Loss or theft of equipment • Cultural constraints. • Insufficient Energy efficiency awareness programs.
Policy Regulatory	• Lack of adequate regulatory scheme to ensure the quality of the energy service. • Lack of energy planning-vision by territorial entities. • No long-term electrification mechanisms. • Absence of sustainable schemes that guarantee the efficiency and sustainability of the projects in the long term. • Lack of incentives for private investors. • Lack of tariff schemes for micro-grid projects. • Lack of legal certainty for better investment climate. • Use of assets owned by the MME, IPSE, or the municipality itself, without any type of remuneration scheme. • Lack of clear definition of project developers' responsibilities.	• Lack of a flexible tariff that adapts to the variability of the payment capacity in the ZNI. • Call for proposals do not facilitate the entry of foreign investment. • No distinction in tariff schemes depending on the project location. • Mayors or local authorities select the service provider. • Regulatory instability (regulation changes that affect the business model). • Lack of coordination between institutions. • Lack of main-grid arrival policy.

According to the National Centre of Monitoring for the ZNI (CNM in Spanish), as of December 2020, more than 50% of the registered operators (94 in total) providing the electricity service and/or developing O&M activities in the ZNI were public entities (CNM-IPSE, 2021). The other operators corresponded to limited liability companies with private or mixed capital (IDB, 2016). One of the main reasons for this low private sector participation is that Capital Expenses (CAPEX) of diesel-powered systems are much lower when compared with RE-based solutions. Also, while the CAPEX for diesel generation requires an investment payback period of around 2.5 years, the CAPEX for RE alternatives in the ZNI implies an investment payback period of about 8 years (hybrid and solar). At the same time, companies willing to provide O&M activities in these areas face high initial costs of investments that cannot be recovered through the tariff and the subsidy scheme. The electricity costs in the ZNI are very high compared to the costs in the SIN (around US$0.26/kWh compared to US$0.11/kWh, respectively), mainly due to local constraints that hinder the logistics of service provision in a technical, environmental, and economically efficient manner. Some of these aspects are related to the dispersion of the communities, the geographic location of the projects, the lack of local skilled personnel, or local inappropriate infrastructure (i.e. lack of paved roads, water service, and mobile phone network). This scenario explains in large part operators' preference for diesel solutions and thus, justifies the government's interest in providing a better regulatory environment for private sector investments in RE in the ZNI.In addition, as highlighted by the interviewees, the average revenue per user (ARPU) is a key measure to evaluate how much revenue the company is generating for each active customer. Off-grid service providers have low debt capacity due to unpredictable revenues from customers with non-recurring incomes. Another important issue affecting the company's revenues is the percentage of inactive or lost customers or customers discontinuing their subscriptions within a given period, namely the customer churn rate (CCR) which represents a high portfolio risk. Normally, off-grid service providers work to maintain a low CCR (OEP 2).

Another issue is related to the risk perception of first-tier financial entities. As presented in IDB (2015), financial institutions *"lack the capacity to market, analyse and structure* RE *deals. They are uncertain about their returns and losses, and often require guarantees of debt repayment".* As a result, off-grid project developers need to present enough evidence of their financial capacity when asking for medium or long-term loans. If the potential project is partly funded with debt, the lenders expect interest payments on the debt irrespective of the conditions under which the business is operating. In addition, equity investors for off-grid electrification projects ask for companies' guarantees to ensure a secure stream of revenue to fund operating and maintenance costs, repay project debt, and provide a return to them. As highlighted by OEP1 and OEP3, most venture capital firms aim for a minimum internal rate of return (IRR) of 12-14% for off-grid electrification projects.

In addition, the lack of a clear definition of how much of the project operating cost is a fixed cost and how much is a variable cost impacts the uncertainty regarding the level of debt the investor needs to make, affecting the entry operation of private investors, especially those with market operations in other countries.

Regarding the current subsidies scheme, off-grid energy service providers found delays of more than three (3) months in the subsidies' payment. Subsidy instability impacts not only the volume of the project (i.e. the number of systems to be installed) but also user satisfaction and confidence (See Bekker (2010)).

Technical challenges. Historically, there has been limited use of RE sources in the ZNI and as a result, nearly 88% of the current installed capacity depends on diesel-powered generation plants (IPSE, 2022)**.** In addition, the provision of electricity service in the ZNI continues to be limited to a few hours (4 to 5 hours a day) in 86% of the localities (CNM-IPSE, 2021), which is a critical barrier to local well-being and socio-economic development. Unfortunately, according to the 2020 report released by the SSPD, the quality of the electricity service in the ZNI has decreased over the years (SSPD, 2020). For instance, the average daily hours of service in the departmental or municipal capitals (type 1 localities), was 21.10 hours in 2015, compared to 20.60 hours in 2016, and 20.80 hours in 2017. This scenario provides evidence of the deficiencies that local off-grid energy service providers still have in terms of operating and maintaining a service supply under quality criteria. There are no legal consequences or penalties for companies providing a service of low quality and reliability, especially when the service is scattered or attended by more than 90 energy service providers. Many of these existing companies do not have trained personnel for both administrative and technical issues or they do not have enough technical experience in the ZNI (GOV). In some regions of the ZNI, where there is a grid operator in the incumbent area of the projects, off-grid initiatives based on RE decentralised systems (e.g. stand-alone PV systems or isolated minigrids) are not included within the company energy planning expansion. New grid extension projects are feasible when the customers' location is within a radius of 50-100 m from the last circuit of the closest low-voltage network. Implementing off-grid projects is not economically viable for the company.

In addition, historically, due to the special complexity of Colombian geography, it is not always feasible (i.e. due to technical or economic conditions) to implement a satellite monitoring solution and thus, to carry out reliable monitoring of the provision of electricity service in the localities of the ZNI. As a result, the national monitoring system of the ZNI only provides real-time remote monitoring to about 9% of the off-grid localities. The remaining localities (nearly 1621) are monitored through the IPSE's contact centre, which gathers energy data via telephone calls and other communication channels available in these locations (e.g. email, and text messages, among others). Information is provided by people from the communities, grid operators, and government entities that have become "energy informants" (IPSE, 2021c).

Another issue relates to the lack of reliable estimates of the community energy needs which could result in inaccurate system design and configuration. This uncertainty increases the risk perception of potential investors looking for customers who consume enough electricity to guarantee the company's revenues. The lack of prior knowledge about the communities' socio-economic characteristics (i.e. communities in sparsely populated areas) and the geographic conditions of the area to be attended (i.e. topography, weather constraints, lack of paved roads, water service, and mobile phone network) also affects the system design and the number of technical visits required to provide preventive maintenance and the easiness to attend any system failure, which affects the operating costs of the project (i.e. the expenses for maintenance of the systems, salaries, transportation, rents, etc.)

Currently, there are off-grid energy projects in the ZNI with stranded or abandoned assets, that are no longer working because they did not receive enough maintenance, or they need to be replaced. Most of this infrastructure belongs to the MME and IPSE-public institutions that work with limited resources to fund the maintenance or replacement of these systems. Unfortunately, off-grid service providers are not willing to receive these assets because they cannot recover the OPEX with the regulated tariff, including the users' subsidies if previously they have not been granted a CAPEX subsidy for the system installation.

In addition, companies also face the lack of local skilled and qualified potential employees in the projects' location. Thus, hiring "foreign" manpower or technician not only the installation and operation costs of the project but also undermine community acceptance.

Finally, there are no well-defined technical standards or codes for off-grid project operation and equipment requirements. Thus, in some cases, project developers bringing new technologies or more efficient equipment, require prior IPSE's approval to guarantee their technology will not be rejected during the resource allocation process of the FAZNI. In addition, technical requirements are not standardised among the different financial funds, which require additional efforts (i.e. technical and economic) from potential proponents.

Social/Cultural Challenges. Community engagement and participation in the development of RE off-grid projects in the ZNI is a key factor that promotes the long-term sustainability of these projects. The lack of community awareness and acceptance of RE projects affects revenues (GOV). If the community is found unsupportive, the system may face many local challenges such as thieving, damaging, tampering, etc., which affect the company's revenues. This aspect is related to the lack of customer ownership. The link between ownership and theft is widely acknowledged in the literature (Bekker, 2010). In particular, the uncertainty regarding the future occurrence of theft and vandalism affects the operating costs of the project since the investor assumes the system replacement.

Another issue is related to the safety conditions to access the community. Depending on the region, the technical staff staffs need the presence of local police service to commute within the area. Thus, off-grid project financials use a rate of 5%-10% of the total budget to account for contingencies. This will cover any extra costs that might come up, such as any "commission" to armed groups controlling the area of the project.

The uncertainty regarding the customers' ability and willingness to pay for the service affects the financial sustainability of the project. Investors need to account for the fact that customers living in rural areas have lower incomes than their counterparts in cities. However, levels of poverty in populated centres and scattered rural areas of the national territory have increased: according to the National Administrative Department of Statistics (DANE), in 2019, multidimensional poverty (PM) in the capitals of the country was 12.3% (0.9 percentage points less than in 2018), and in populated centres and scattered rural was 34.5% (4.1 percentage points below that registered in 2018) (DANE, 2021).

Culture is a key factor to consider within the structuring and implementation phases of the projects. Projects in ethnic areas require the approval of the local leader(s) to have the community's support through the project implementation. In some cases, this requires additional efforts (i.e. political) to arrange several meetings and dialogues with the community, and also to find someone willing to serve as a translator from Spanish to the native language. Failing to obtain their support does not allow sustainable business schemes to be established.

Policy/regulatory challenges. Colombia and other South American countries face a common challenge that relates to the lack of a georeferenced integrated rural electrification plan that leads the country to achieve universal energy access by 2030 (ACD). The current version of the PIEC 2019-2023 does not integrate a GIS database of the exact location of users lacking access to electricity. Thus, additional resources are required to update the PIEC with updated GIS tools and make validations on the field.

Within the regulatory context, resolutions that govern the electricity provision in the ZNI have created an overly bureaucratic environment rather than facilitating electrification efforts (Garces et al., 2021). In particular, off-grid providers desire a better investment environment with regulated tariffs that guarantee the expected return on their investment and the community desires a low or rather affordable tariff and reliable electricity supply. However, currently, there are concerns about the current tariff regimes associated with different technologies implemented in the ZNI. Stand-alone PV systems technologies are easier to introduce under the current regulatory framework. There is not a clear regulatory tariff for private investors interested in implementing minigrid projects in the ZNI. The current tariff corresponds to the CREG Resolution No. 166-2020, a transitory scheme that estimates the maximum monthly tariff for providing electricity service in off-grid areas (COP$/month), through stand-alone solar PV systems (> 500 Wp, AC) (CREG, 2020a). Instead, minigrid developers need to request the approval of a monthly tariff from the CREG and this process can last between six and nine months (OEP4).

The regulations privilege territorial entities for the provision of the service (art. 6- Law 142 of 1994), but most of them lack adequate knowledge and experience in structuring off-grid projects. Thus, when technical proposals are revised by IPSE to obtain technical feasibility, some of these projects fail to meet the technical, administrative, financial, environmental, and legal requirements to be presented at the FAZNI committee. In addition, companies interested in developing projects require permits from the territorial entities, which in some cases difficult for the progress of the projects or favoured particular projects (i.e. corruption).

Off-grid energy providers also are exposed to institutional barriers and government instability. This is, the support from the government is not expected to change in the future or rural electrification policies continued to be fostered and implemented despite the arrival of a new government regimen. This is aligned with the lack of a long-term vision of integrated planning for the off-grid electrification sector.

In addition, foreign companies seeking to set up operations in the Colombian off-grid market need to comply with several extra-financial and legal requirements that difficult or undermine their interest in participating in national calls for proposals. As a result, some of them have opted for joining consortiums or temporary unions with local counterparts.

5.2. Chapter Summary

Off-grid electrification is essential to achieve universal access. However, several characteristics associated with the provision of electricity service in off-grid areas result in higher variability and make electricity expansion particularly challenging. Within this scenario, during the last decades, national programs, plans, and projects have focused on reaching this goal. As a result of this effort, national electrification rates have increased from 76.1% in 1995 to 96.5%, in 2018 (UPME, 2019b). However, the largest deficit is still present in rural areas, where the electrification rate corresponds to 86.54%, compared to an electricity service coverage of about 99.51% in urban areas (UPME, 2019a, 2019b).

In this chapter, following discussions with multiple stakeholders and experts involved in the off-grid sector of Colombia, a set of challenges grouped into four dimensions, namely financial/economic, social/cultural, technical, and policy/regulatory was identified. Key barriers preventing Colombia from achieving universal access by 2030, especially in the ZNI, are mainly related to: (i) exclusive dependence on public resources and limited public resources; (ii) limited participation of private capital in rural electrification projects due to the socio-economic and topographic characteristics of rural areas; (iii) high logistics (i.e. O&M costs) costs due to a high dispersion of the population that hinders the provision of the service; (iv) technical deficiencies (i.e. of local authorities and/or local service providers in rural areas) in the formulation and structuring of rural electrification projects applying for public funds; (v) lack of socio-economic and energy information associated with the rural electrification projects; (vi) local energy service providers have weaknesses in their capacity to manage, operating and maintaining the infrastructure under quality criteria; (vii) limitations in the regulatory framework associated with the quality requirements of off-grid electrification projects; and (viii) high risk perception from potential private service providers due to the low payment capacity of users living in rural and remote areas.

Overall, these insights are crucial within the definition of sustainable rural electrification programs and policy guidelines because they provide a better understanding of the regulatory, financial, economic, social, and technical needs to guarantee the long-term sustainability of off-grid projects.

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6. Universal Electricity Access: Prioritising the poor

This chapter focuses on the social dimension of the sustainable planning framework proposed in this thesis. Understanding the social perspective in planning rural electrification programs is a necessary condition to achieve the desired sustainable energy development in the communities. Within this context, it is critical to guarantee that the poorest areas are being prioritised in the rural electrification agenda. Thus, this chapter provides an overview of the main criteria used by the public sector to allocate public funds, namely, to implement rural electrification projects. As a case study, this chapter mainly analyses whether rural electrification programs in Bolivia are reaching the poorest households.

6.1. Using the UBN index to guide electrification policy in Bolivia

Overall, in South America, different countries rely on specific indicators for national development planning, including energy planning: while Brazil uses the PL and the HDI, Bolivia, and Peru rely on the Poverty Line (PL) and the UBN index (CEPAL, 2012; Gómez and Silveira, 2010; Instituto Nacional de Estadística e Informática (INEI), 2017; Instituto Nacional de Estadística (INE), 2017; Slough et al., 2015).

Since 1976, the Bolivian government has estimated the UBN index through the data obtained from the national Censuses of 1976, 1992, 2001, and 2012 (Instituto Nacional de Estadística (INE), 2017). Thus, this measure of poverty has been a key criterion to guide funds allocation within policies for poverty alleviation and thus, to succeed in reaching the poor and improving their lives (Santos, 2014). For instance, the PEVD program has guided Bolivia's rural electrification policy to identify areas where issues of poverty, social exclusion, and access to basic population services represent a priority (VMEEA, 2008b). Figure 6.1 shows the location of the PEVD's areas of influence and their corresponding 2001 and 2012 UBN indices.

State	2001 UBN index (%)	2012 UBN index (%)
PO	79.7	59.7
BE	76	58.8
PA	72.4	55
CH	70	56.4
OR	67.9	47.0
LP	66.2	45
CO	55	45.5
TA	50.8	34.6
SC	38	35.5

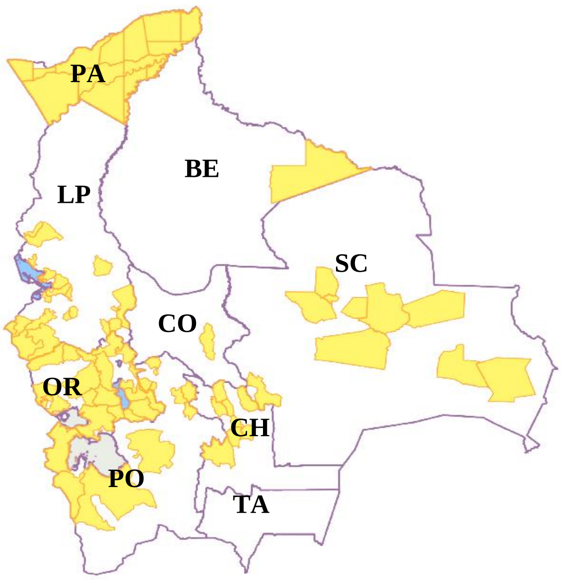

Figure 6.1 Location of Bolivian states under the PEVD program: PA (Pando), BE (Beni), SC (Santa Cruz), OR (Oruro), LP (La Paz), PO (Potosi), CH (Chuquisaca), TA (Tarija) and CO (Cochabamba), and their corresponding 2001 and 2012 UBN indices. Source: Adapted from (VMEEA, 2008b).

The process to calculate the UBN index follows five main stages as presented in (Feres and Mancero, 2001; Instituto Nacional de Estadística (INE), 2001a). First, identifying a set of indicators of deprivation, *i,* within some dimensions that vary among countries: Colombia and Venezuela use 5, Paraguay uses 7 and Bolivia uses 10 (Hicks, 2000). Thus, this indicator is not comparable among countries. Second, setting a minimum normal range, X_i^*, for each indicator (values below this level denote deprivation). Based on these thresholds, the variable measured through the census, X_{ij}, is transformed into an index number: $UBN_{ij}^* = \frac{X_i^* - X_{ij}}{X_i^*}$, reflecting the unsatisfied basic need for each indicator *i* and household *j*. Third, for each dimension, a composite index is estimated based on the geometric mean of the indices for each indicator. Fourth, dimensions are grouped within four broad areas representing a basic need: 1) Housing; 2) Basic services; 3) Education and 4) Health(Instituto Nacional de Estadística (INE), 2017). Finally, the overall UBN index score for each household is estimated as the geometric mean of the UBN indices for each basic need, as shown in Figure 6.3.

In Bolivia, the VMEEA is the institution that defines the criteria for prioritization and eligibility for rural electrification projects and controls these projects' implementation. This chapter is focused on exploring the key criteria the Bolivian government has considered to achieve this purpose. During the last decades, the GoB has relied on the support of different international institutions to develop strategies for the energy sector. Between 1998 and 2000, the Joint UNDP/World Bank Energy Sector Management Assistance Program (ESMAP) assisted six Bolivian states (i.e. La Paz, Oruro, Santa Cruz, Cochabamba, Chuquisaca, and Potosi) in the planning and analysis of rural electrification projects (UNDP/World Bank Energy Sector Management Assistance Program (ESMAP), 2005). As a result, the program defined three main criteria for prioritising rural electrification proposals: The project should have a positive Net Present Value (NPV) for social benefits. An operator should be responsible for the operation and maintenance of the project; and the project should decrease by at least 15 percent the production costs of local industry (e.g. mills, water pumping, stations, grain producers).

According to the ESMAP's report, the fulfilment of these criteria is essential for the VMEEA to support or finance the proposals submitted by the states. As a result, a manual for rural electrification projects was prepared and is now used by most states and consulting firms, contributing to expediting the approval and execution of new rural electrification projects (UNDP/World Bank Energy Sector Management Assistance Program (ESMAP), 2005).

In addition to the ESMAP support, in 1998, the GoB officially requested technical assistance from the Japanese Government to define a rural electrification plan upon different energy supply technologies. In response to this request, the Japan International Cooperation Agency (JICA) formulated a plan for the period 2002-2011 (Japan International Cooperation Agency, 2002). Within the plan, the grid extension was defined as the main strategy for rural electrification in Bolivia, as it is also confirmed by the 2025 National Plan for the Bolivian electricity sector. As a result, the JICA proposed three criteria to identify and prioritise candidate projects for grid extension, as shown in Figure 6.2.

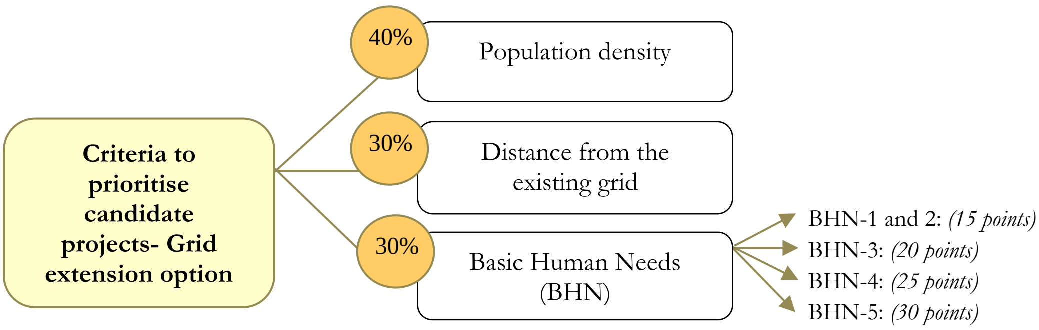

Figure 6.2 Criteria to prioritise rural electrification projects for grid extension. Source: Authors, adapted from (Japan International Cooperation Agency, 2002)

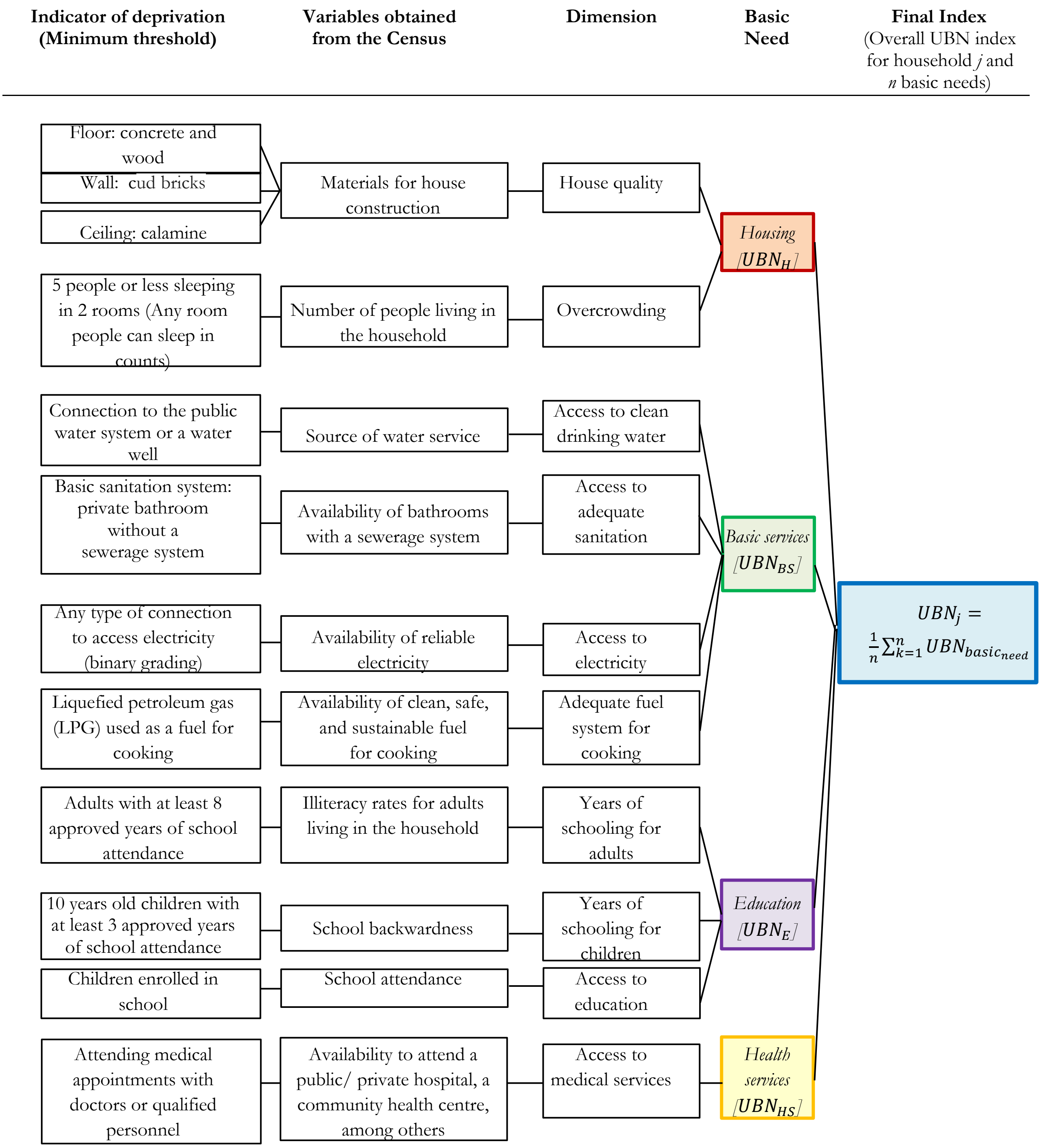

Figure 6.3 Algorithm for the UBN index computation in Bolivia. Source: Author's compilation based on (Instituto Nacional de Estadística (INE), 2017)

Out of the three criteria, the highest percentage was given to the population density (i.e. 40%) as the grid line extension required a relatively concentrated population to be electrified. The other two criteria (i.e. the distance from the existing grid line and the indicator for basic human needs) received an individual score of 30 percent. In particular, the breakdown for the BHN criterion had four score options: the higher level of poverty was in the municipality, the higher the score assigned in this category and thus, the most assistance was required.

However, for isolated rural areas, where grid extension was not the most economic option, the JICA's plan considered three types of energy systems: micro-hydro power generation, wind generation, and solar PV generation. Only those projects with competitive costs compared to the grid extension were finally selected as the priority projects to be included in the Rural Electrification plan. Thus, projects were selected only if the energy cost was competitive with that of grid extension. For ranking the selected priority micro-hydro, wind, and solar PV energy projects, the JICA applied different criteria. Regarding the selection of priority areas for solar PV projects, where no other renewable energy sources were available, sites were selected using the criteria presented in Figure 6.4.

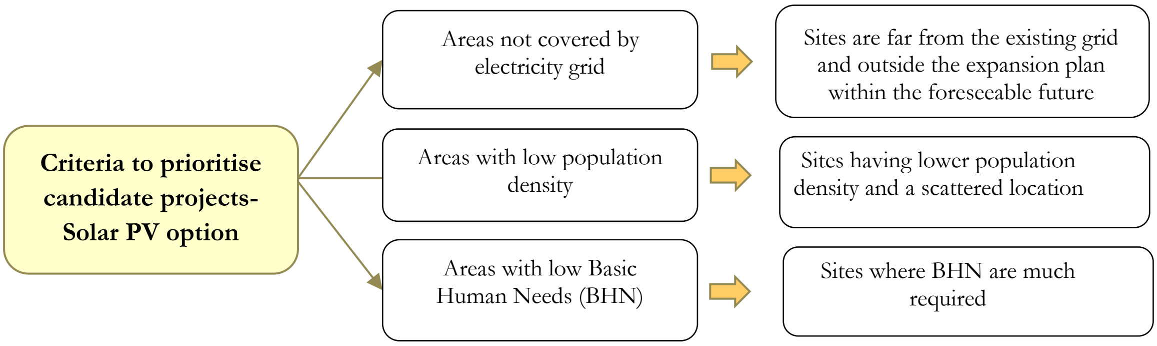

Figure 6.4 Criteria to prioritise rural electrification projects based on solar PV generation. Source: Authors, adapted from (Japan International Cooperation Agency, 2002)

Applying the above criteria, scores were estimated for all the selected priority projects. Based on the results and through discussion with the Vice-Ministry of energy and the states, projects were divided into two phases: Phase I to be implemented during 2002 - 2006 and Phase II from 2007 to 2011 (Japan International Cooperation Agency, 2002).

6.2. Results and discussion

This chapter presents the results of the descriptive analysis applied to the case of Bolivia. It describes whether electrification programs such as the PEVD targeted the poorest region (in urban and rural areas) based on the UBN index. As abovementioned, this massive program was set up in 2008, but the period for the project's implementation varies from 2011 to 2021.

Based on the 2001 Census, the three poorest states corresponded to Potosi, Beni, and Pando. The highest poverty rate was in the state of Potosi, which also corresponded to the state with the highest percentage of the rural population (66.3%) and the lowest electricity access rate (40.4%). These areas have been included in the PEVD program in different proportions, as presented in Figure 6.1. While all municipalities of Pando-the state out of the national interconnected energy system- are covered by the program, only one municipality of Beni is included in the PEVD program, under the PERER project (See Table 6.1). Besides, of the nine projects of the program, three of them are under implementation in the state of Potosi (See Table 6.1). This difference could be explained based on the indicators presented in Table 6.1. In terms of electricity access and level of poverty, the three states are in the top three positions. However, there is a clear variation in the percentage of the rural population in each state: while Potosi and Pando are mainly rural areas (more than 50% of the population), only about 27% of the population in Beni is considered rural. In contrast, the states of Tarija, and Cochabamba have the lowest inclusion in the PEVD program. These states not only are among the three states with the lowest levels of poverty and highest levels of development (in terms of the UBN index and the HDI) but also, have the highest rates of electricity access.

Results from the 2012 Census show that poverty rates in Bolivia (based on the UBN index) decreased from 58.6 % in 2001 to 46.3 % in 2012 as presented in Table 6.1. At the municipality level, 331 out of the 339 municipalities saw reductions in their UBN index (Andersen and Jemio, 2016; Instituto Nacional de Estadística (INE), 2017, 2012, 2001b). The states of Potosi, Pando, and Chuquisaca continue to have the highest percentage of the rural population and at the same time, they correspond to the states with the lowest rural electrification access, as of 2012 (See Table 6.1.). In contrast, Santa Cruz was the state with the highest electrification rate and corresponded to the state with the lowest percentage of the rural population. Therefore, as suggested in Figure 6.5, the higher the percentage of the rural population in a municipality, the higher the percentage of people lacking access to electricity.

Table 6.1 Bolivia's national indicators between 2001 and 2012. Source: Authors' compilation from (Unidad de Análisis de Políticas Sociales y Económicas (UDAPE), 2012).

State	Total Population	Pop. density (inh/km²)	% of Population (2012)		The UBN Poor (%)[a]		HDI	Electricity Access (EA) (%)			Δ EA (%)	Δ EA (%)
	2012	**2012**	**Urb**	**Rur**	**2001**	**2012**	**2001**	**2001**	**2012**	**2018**	**2001-2012**	**2012-2018**
Potosi	828,093	7.7	40.6	59.4	**79.7**	**59.7**	0.52	**40.4**	74.3	87.6	**+33.9**	**+11.8**
Beni	422,008	2.0	73.1	26.9	**76.0**	**58.8**	0.62	**54.6**	83.7	87.6	**+29.1**	+1.9
Pando	110,436	1.7	48.7	51.3	**72.4**	55	0.60	**45.7**	71.8	83.1	**+26.1**	+1.2
Chuquisaca	581,347	11.3	48.7	51.3	70	**56.4**	0.57	47.2	68.5	88.1	+21.4	**+20.0**
Oruro	494,587	9.9	64.0	36.0	67.9	47.0	0.64	60.6	83.1	87.9	+22.4	**+6.9**
La Paz	2,719,344	20.9	66.7	33.3	66.2	45	0.59	65.8	86.0	95.7	+20.3	+1.3
Cochabamba	1,762,761	31.7	68.1	31.9	55.0	45.5	0.62	68.1	85.4	90.0	+17.2	-4.5
Tarija	483,518	12.9	65.0	35.0	50.8	34.6	0.64	69.2	91.3	96.8	+22.1	-0.3
Santa Cruz	2,657,762	7.2	81.3	18.7	38.0	35.5	0.66	76.1	92.0	95.4	+16	+0.1
Bolivia (Total)	10,059,856	9.3	67.5	32.5	58.6	46.3	0.61	64.4	85.4	92.8	+21	+2.3

(a) Percentage of poor population based on the UBN approach

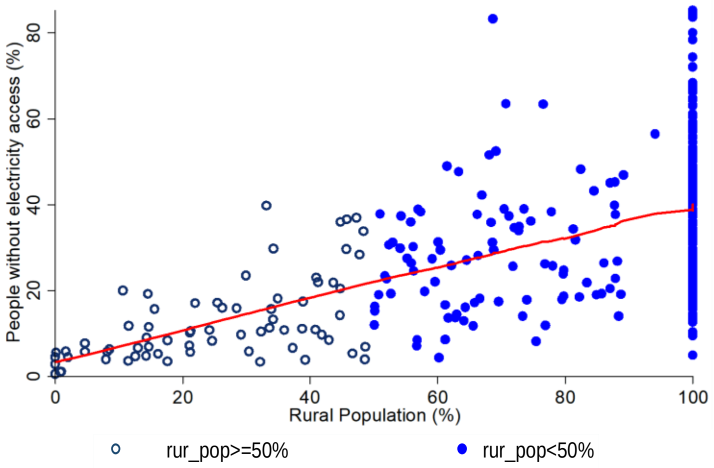

Figure 6.5 Relationship between the percentage of rural population and people without electricity access in Bolivia (2012). The orange line presents the lowess regression that fits the data. Source: Author's compilation from (Instituto Nacional de Estadística (INE), 2012, 2001b; Unidad de Análisis de Políticas Sociales y Económicas (UDAPE), 2012)

However, results present an increase greater than 20% in electricity access (between 2001 and 2012), in states (e.g. Beni, Oruro, and Tarija) with a high level of urban population (> 50%). This could suggest that prioritisation is not only given to rural areas but the location of the poorest communities and thus, programs are also focused on these areas. In particular, Oruro and Beni (in less proportion) are covered by the PEVD program.

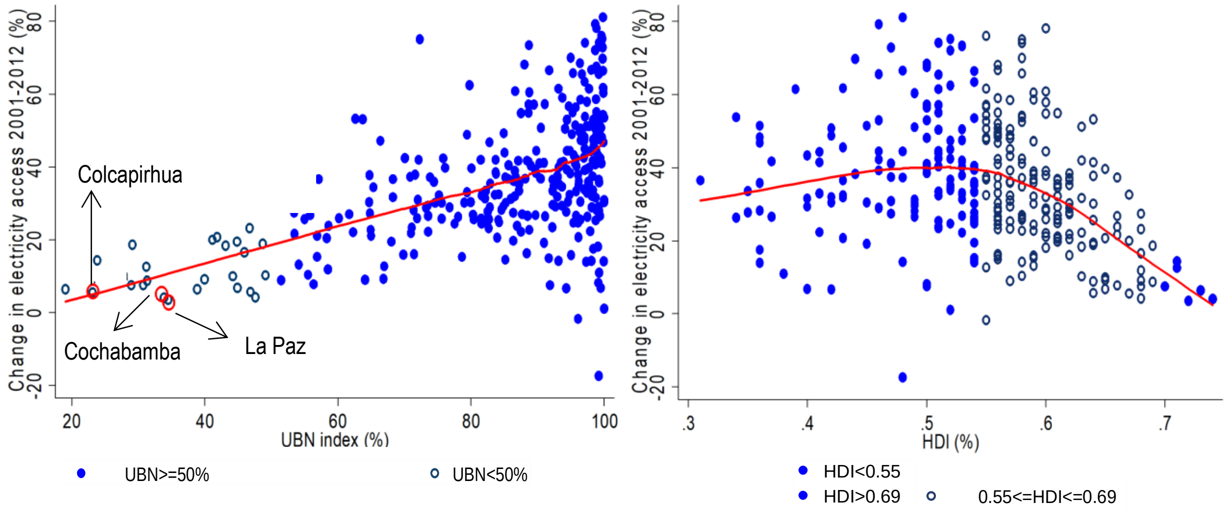

Figure 6.6 a) 2001 UBN index and variation in households' electrification rates between 2001 and 2012 by municipalities, b) 2001 HDI and variation in households' electrification rates between 2001 and 2012 by municipalities. The red line presents the lowess regression that fits the data. Author's compilation from (INE (2012, 2001b), UDAPE, (2012)).

Based on the Censuses of 2001 and 2012, it is found that the poorest states for 2001 (Potosi, Beni, and Pando) experienced the largest gains in electrification between 2001 and 2012 (See Table 6.1). This association shows that high initial levels of unsatisfied basic needs are linked with electrification improvement. This provides indicative evidence that programs such as the PEVD have relied on the municipal UBN index as one criterion for determining which communities to prioritise among candidate municipalities, rather than merely counting on the electricity access rate. In particular, the state of Potosi (the poorest state) experienced the greatest improvement in electricity access and at the same time one of the greatest reductions in the UBN index. This result replicates when considering all the municipalities, as presented in Figure 6.6 a). The graph suggests that there is a link between improvement in electricity access and poverty rates in Bolivia, namely that the poorer the municipality was by 2001, the higher the improvement achieved in electricity access by 2012.

On the other hand, among the three poorest states for 2012 (Potosi, Beni, and Chuquisaca), Chuquisaca and Potosi experienced the largest gains in electrification between 2012 and 2018 (See Table 6.1), followed by the state of Oruro, rather than Beni or Pando (states with a higher percentage of UBN poor). One explanation relies on the difference in population density of each area, and its effects on the eligibility criteria for grid extension projects. As presented in Table 6.1, the state of Oruro has a higher population density than Beni and Pando, which represents a higher score and eligibility for grid extension projects. These results are aligned with the 2025 National Plan for the Bolivian electricity sector, which states that in rural areas, 70% of the projects will rely on extending the grid and only 10% on the installation of off-grid renewable energy systems (i.e. minigrids and stand-alone generation systems). This means that prioritising electrification projects will depend mainly on the population density of the community rather than on the level of poverty. In consequence, additional investments should focus on increasing electricity access rates in Potosi, Pando, and Beni, the states with the lowest values of density population (See Table 6.1) and where levels of electricity access continued to be below 90% (as of 2018) (See Table 6.1) (Instituto Nacional de Estadística (INE), 2018).

Figure 6.6 a) also shows that municipalities with a low UBN index in 2001 were more likely to have already achieved high rates of electrification by 2001. As a result, there was relatively less room for improvement in these municipalities. For instance, as marked in Figure 6.6 a), La Paz, Cochabamba, and Colcapirhua corresponded to the three municipalities with the lowest improvement in energy access for 2012 (less than 6%), but in 2001, these areas already had electricity coverage over 93% (Instituto Nacional de Estadística (INE), 2012, 2001b; Unidad de Análisis de Políticas Sociales y Económicas (UDAPE), 2012).

In contrast, Figure 6.6 b) shows the comparison between the 2001 Human Development Index and the improvement in electricity access from 2001 to 2012, in 313 municipalities of Bolivia. Based on the HDI, 54.6% of the municipalities exhibited a medium development level, 52.7% had a low development level and only 1.9% had a high development. Results from Figure 6.6 b) suggest that in contrast to the UBN index, there is no clear relationship between the improvement in electricity access for the period of 2001-2012 and the HDI. These statistics primarily make the point that a high proportion (54.6%) of the rural population is associated with medium human development indicators. Eight out of the nine Bolivian states had a medium development level in 2001 and not all the least developed municipalities (according to the HDI measure) corresponded to the UBN poorest municipalities, as presented in Table 6.1. Therefore, using the HDI to prioritise where to carry out electrification programs would not necessarily have targeted municipalities with the lowest electricity access. However, it is important to highlight that the HDI in Bolivia has grown from 0.535 in 1990 to 0.693 in 2017, which corresponds to an increase of about 22% (UNDP, 2018), which evidences the effect of recent policies in reducing poverty in the country.

In Bolivia, there are no official poverty indicators that combine income measures and quality of life variables to measure a multidimensional phenomenon. Castellani and Zenteno (2015) (Castellani and Zenteno, 2015) proposed an approach to estimate the MPI for Bolivia. In consequence, this indicator could be used in the country as a tool for the allocation of future electrification projects, monitoring regional policies, and defining goals for specific interventions. It could "complement traditional basic needs and income-based poverty measures by capturing the deprivations that each person faces at the same time concerning education, health, and living standards. The more policy-relevant information there is available on poverty, the better-equipped policymakers will be to reduce it" (OPHI, 2018).

6.2.1. Prioritising rural areas for public funds allocation: the case of Colombia

In addition to Bolivia, other countries in Latin America and the Caribbean (LAC) have a long tradition of multidimensional poverty measurement within the Basic Needs Approach (BNA) (Hicks, 2000). However, this approach has also received criticism because one deprivation alone may not represent poverty. In addition, it requires updated information from censuses, but this is not always possible since censuses are conducted every five to ten years, depending on the country. In consequence, the availability of household surveys, regularly implemented in LAC countries, has made it possible to gather more recent information, and therefore, to use other methods to measure poverty and development, such as the MPI and the HDI (Santos et al., 2015).

As it is mentioned in Chapter 6, in 2011, the GoC launched a Colombian Multidimensional Poverty Index (C-MPI), based on the Alkire-Foster method, which is used to monitor public policies by sector, design poverty reduction goals, track progress, and set specific targets. It includes, among others, "dimensions regarding early childhood and youth conditions, access to health services and labour conditions, variables that had not been included in previous multidimensional indices" (Salazar et al., 2013, p.5).

However, despite the BNA limitations, the UBN index is still used in Colombia to prioritise public resources from the FAER, which finances rural electrification projects aimed at providing electricity service to rural households under the grid extension or the grid densification/intensification scheme. Since 2016, the MME defined the Resolution No. 41039 of 2016, which sets a methodology to allocate resources coming from the FAER, as presented in Table 6.2.

Under this methodology, potential projects are ranked and prioritised for implementation, accounting not only for economic weighting factors, such as the total cost per user but also for social indicators such as the UBN index, which has a total weight of 20% on the overall score (MME-Colombia, 2016a). The FAER committee selects the most attractive project, based on an order of eligibility (OEP_i) formulated by Equation (6.1). In contrast, the FAZNI committee allocates the FAZNI resources based on a priroritisation methodology set in the MME resolution No. 41208 of 2016 and formulated in Equation (6.2). In both cases, the selection process depends on the projects to be implemented in areas affected by the Colombian conflict, the total cost per user of each project, and the impact of the project, measured by the number of total beneficiaries or newly connected users.

Table 6.2 Comparison of Colombia's public policy to prioritise public funds in the SIN and the off-grid zones. Source: (MME-Colombia, 2016a, 2016b)

FAER: Fund for the electrification of interconnected rural areas	FAZNI: Financial support fund for the electrification of non-interconnected areas
$OEP_i = \frac{UBN_B}{UBN_A}(20\%) + \frac{UN_B}{UN_A}(40\%) + \frac{UE_B}{UE_A}(10\%) + \frac{CxU_A}{CxU_B}(20\%) + Mpeace(10\%)$ Equation (6.1)	$OEP_i = \frac{UN_B}{UN_A}(40\%) + \frac{UE_B}{UE_A}(15\%) + \frac{CxU_A}{CxU_B}(20\%) + FNCER(15\%) + Mpeace(10\%)$ Equation (6.2)

Where:
UBN_B is the Unsatisfied basic needs index of the potential community of project i
UBN_A is the highest UBN index among all the projects under evaluation
UN_B corresponds to the total new users who benefited from each project i under evaluation
UN_A corresponds to the highest UN_B among all the projects under evaluation
UE_B is the current number of users benefited from each project i under evaluation
UE_A corresponds to the highest UE_B among all the projects under evaluation
CxU_B is the total cost per user of each project i
CxU_A corresponds to the lowest CxU_B among all the projects under evaluation
FNCER corresponds to non-conventional renewable energy resources. A value of 1 is assigned to this term if the project includes at least one type of renewable energy system (i.e. solar, wind, geothermal, etc.). Otherwise, a value of 0 is assigned.

$Mpeace$ stands for "Municipality of Peace". A value of 1 is assigned to this term if the project includes at least one municipality directly affected by the armed conflict or prioritised under the post-conflict national program. Otherwise, a value of 0 is assigned.

However, there are differences regarding the inclusion of a measure of poverty between both funds. In particular, the FAZNI which provides financing to projects in off-grid zones does not consider the UBN index. One explanation is related to the fact that more than 77% of the population located in the off-grid zones is considered poor based on the UBN index (IPSE, 2015), namely, they are deprived in at least one dimension of the BNA. This high proportion provides evidence of the homogeneity in the level of poverty in the off-grid areas. Thus, using the UBN index does not necessarily offer distinctive information to prioritise where to carry out electrification programs in these remote rural areas.

In contrast, the MPI method considers that households in a situation of poverty are those with deprivation in at least 33.3% of the 15 indicators grouped in the following five (5) dimensions: educational conditions of the household, conditions of children and youth, health, housing conditions, and access to household public services (DNP, 2020). In consequence, including the MPI in the FAER and FAZNI prioritisation approach could contribute to targeting the poorest areas. In addition, the MPI is already being used as a public policy tool in the Colombian context to track deprivations across the country, monitor public policies by sector, and design the poverty reduction goals of the National

Development Plan (Salazar et al., 2013). In fact, it has been used to prioritise differentiating conditional transfers for the program *"Mas Familias en Acción"* across regions. Also, new poverty maps for Colombia have been constructed from the information obtained, which have become a source of information for geographic targeting (Salazar et al., 2013).

Thus, there is information available about the trends of poverty rates within the whole country and across urban and rural areas. According to (Salazar et al., 2013), there is a clear imbalance between urban and rural areas in terms of poverty and quality of life. Urban areas have a lower percentage of multidimensionally poor people than rural areas.

6.3. Chapter summary

This chapter provided an overview of the prioritisation methodologies implemented in Bolivia and Colombia to allocate public funds. It revealed that the BNA is considered one of the main social indicators used to monitor poverty (Feres and Mancero, 2001; Hicks, 2000). This chapter analysed the suitability of using the UBN index as the social criterion to select the areas that should be prioritised for rural electrification projects. This study draws on data provided by local Bolivia's Censuses of 2001 and 2012. Based on graphical analysis, this chapter also describes the association between the 2001 UBN index and the improvement in rural electrification access of Bolivian municipalities between 2001 and 2012. This process was repeated to also identify the UBN poor by 2012 and confirm if these communities had the largest gains in electricity between 2012 and 2018. Results suggest that Bolivia's poorest states, namely those having the highest UBN indices for 2001, experienced the largest improvements in electrification between 2001 and 2012. However, using complementary socio-economic indicators, such as the Multidimensional poverty index (MPI) could complement the traditional UBN index by capturing more relevant information that could lead to more accurate poverty measurement and rural electrification interventions, not only in Bolivia but also in Colombia.

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7. The concept of long-term sustainability in off-grid projects: The private sector's perspective

This chapter identifies the key factors that determine the long-term sustainability of off-grid electrification projects in rural and remote communities considering the private sector's point of view. Using a multi-criteria decision-making (MCDM) method based on the Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH), 13 criteria, within 5 dimensions were defined. This chapter provides an overview of the main criteria influencing the decision-making of deciding where to invest in rural electrification projects with stand-alone PV systems. As a case study, this chapter mainly analyses whether Bolivia, Peru, and Colombia represent a sustainable option for a potential private investor willing to implement off-grid solar PV projects. As a result, the compiled information was used to identify and rank locations that fulfil the required criteria for the selected off-grid solution.

In this chapter, the application of this multi-criteria model is illustrated by evaluating the performance of three potential off-grid sites (i.e., Bolivia, Peru, and Colombia) to implement off-grid solar PV projects. Special attention is given to the following questions: Which factors determine the long-term sustainability of off-grid electrification projects in rural and remote communities? and Which region represents the most sustainable option for implementing off-grid solar PV projects? To provide some answers, the model was calibrated following a participatory process with the input of a DM with extensive experience in the rural electrification sector. As a result, a set of sustainable dimensions and key criteria that influence the decision-making of selecting the most appropriate locations to implement off-grid solar PV projects were identified. In addition, the concept of sustainability assessment for site selection was considered by estimating a composite score that groups each alternative into three categories: Highly sustainable (score > 100), Sustainable (0 < score < 100), and Unsustainable (score < 0), considering that each place offers a different level of attractiveness of investment for the DM.

The obtained results offer guidance to investors seeking to identify the most suitable sites for implementing off-grid solar PV projects in rural and remote areas while accounting for sustainable criteria. Also, these results can help policymakers to identify and prioritise geographical areas for the provision of electricity access in developing countries.

7.1. Multi-Criteria Modelling

In the present study, the MACBETH approach is applied to evaluate the performance of three potential locations for implementing off-grid solar PV projects in terms of a set of key criteria defined by the DM.

Figure 7.1 illustrates the main phases of the multi-criteria modelling implemented in this study.

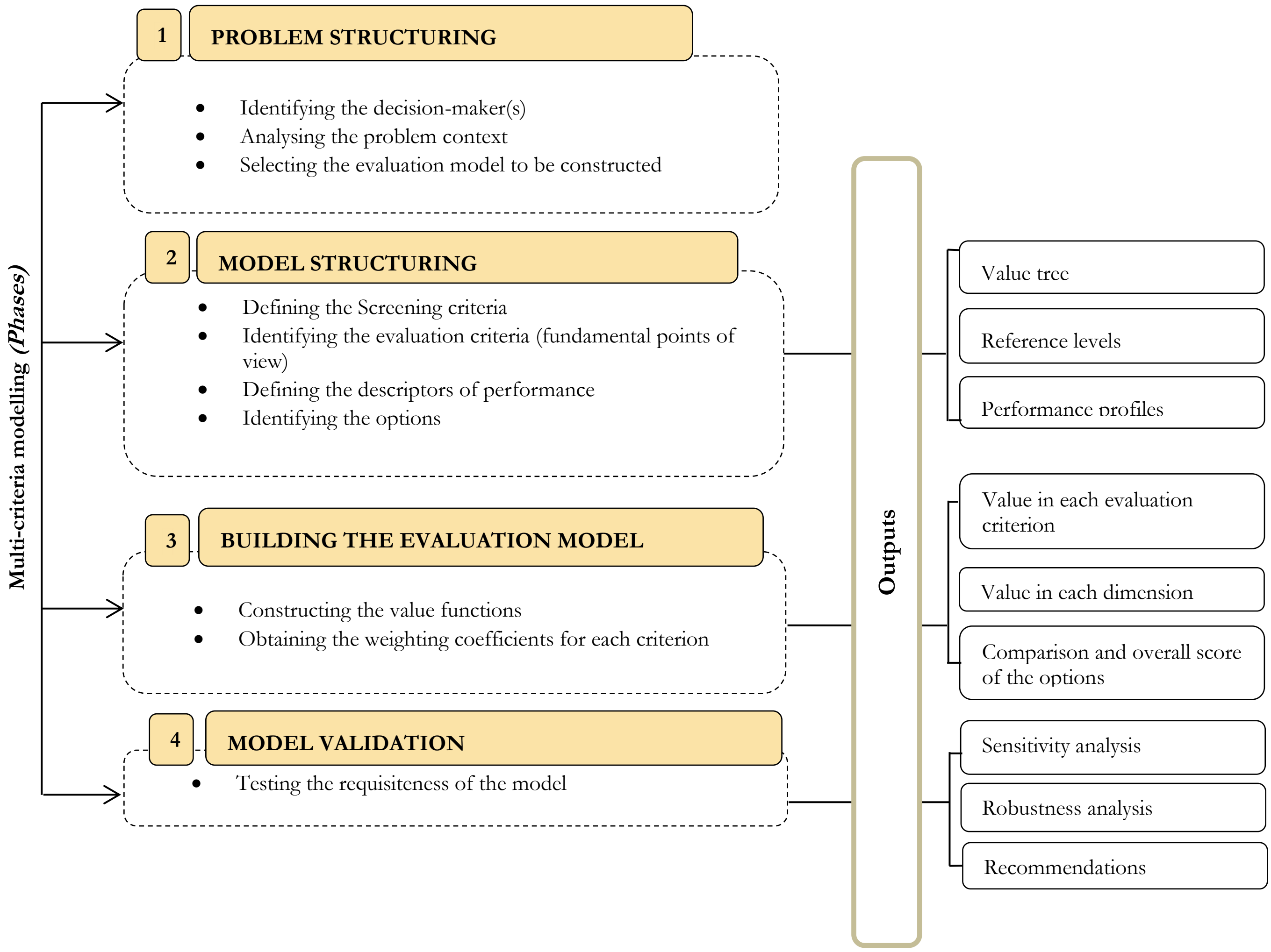


Figure 7.1 Schematic overview of the MACBETH approach and associated outputs. Source: Adapted from (Bana e Costa et al., 2012, 2008).

7.1.1.1. Problem and Model Structuring

As mentioned above, private firms face the decision problem of evaluating options for expanding their operations to other countries. In a setting where uncertainty is the norm, decision-makers seek information that enables them to select a foreign market from a set of possible alternatives, based on different aspects that guarantee the sustainable operation of a particular project, providing provide a favourable investment environment for the investor. Relevant criteria concerning this choice include, for instance, the level of poverty in the region, and the political and economic environment of the countries, among other aspects. Therefore, a MCDM is technically adequate for dealing with this problem (Bana e Costa et al., 2016; Burton and Hubacek, 2007; Montignac et al., 2009).

To illustrate the real-world application of the MCDM model, the MACBETH approach and software evaluate the performance of three potential locations for implementing off-grid solar PV projects in developing countries. Following a participatory process, the model was calibrated with the input of a decision-maker (DM) with extensive experience in off-grid energy projects (a co-founder and former CEO of Kingo (Kingo is a Guatemalan off-grid provider of prepaid solar energy that has installed over 50,000 solar home systems (SHS) in off-grid communities of Guatemala and Colombia, between 2013 and 2020) (Rodriguez, 2020). Thus, these judgements represent the point of view of a private company that makes investments in the rural electrification sector of developing countries. The point of view of other stakeholders, including academia, governments, or NGOs, are not considered in this study.

After defining the decision problem and its context, the following step was to define the screening criteria (i.e., any process that reduces a large set of alternatives to a smaller set that (most likely) contains the best choice (Chen et al., 2008)). During the meeting with the DM, a preliminary screening analysis to select or reject possible options was performed. In this case, based on the company's commercial experience and the 2018 electricity access rates (acceptance criterion), the three South American countries with the lowest rates of rural electrification, namely Bolivia, Peru, and Colombia, were selected as suitable alternatives to implement off-grid solar PV projects (See Table 7.1). These locations also represent interesting business opportunities for off-grid companies since there has been a strong commitment from the local governments to implement national policies, regulations, and programs aiming at increasing the electricity provision in rural and remote communities mainly through stand-alone PV systems and the grid extension (Eras-Almeida et al., 2019; Gaona et al., 2015; Hinestroza-Olascuaga et al., 2021). The greatest cases correspond to Bolivia and Peru, where rural electrification rates increased by about 65% between 2000 and 2018 (World Bank, 2018). In the Colombian context, as of 2020, there were about 13,000 stand-alone PV systems installed in off-grid areas of the country. In addition, it is estimated that about 4821 rural and remote households will receive electricity service through this type of energy solution by 2021 (CREG, 2020a). Table 7.1 presents a comparative review of the key development indicators between the three countries.

Within each country, three states were selected for the sustainability assessment (see Figure 7.2): La Guajira (Colombia), Loreto (Peru), and Pando (Bolivia). These regions have the lowest electricity access rate in each selected country: 58.81%, 76.6%, and 83.1%, respectively (INE, 2019; INEI, 2019; UPME, 2019b).

This thesis considers the specific case of Bolivia, Peru, and Colombia, the three South American countries with the lowest electricity access rates. These locations also represent interesting business opportunities for off-grid companies since there has been a strong commitment from the local governments to implement national policies, regulations, and programs aiming at increasing the electricity provision in rural and remote communities mainly through stand-alone PV systems and the grid extension (Eras-Almeida et al., 2019; Gaona et al., 2015; Hinestroza-Olascuaga et al., 2021). The greatest cases correspond to Bolivia and Peru, where rural electrification rates increased by about 65% between 2000 and 2018 (World Bank, 2018).

Regarding the type of energy technology solutions, special attention is given to decentralised solutions (i.e. stand-alone systems and minigrids) implemented in off-grid areas, since extending the grid is not an economically viable option to reach the last-mile customers. In the Colombian context, as of 2020, there were about 13,000 stand-alone PV systems installed in off-grid areas of the country. In addition, it is estimated that about 18,000 rural and remote households will receive electricity service through this type of energy solution by 2022. Peru has implemented a massive program for stand-alone electricity systems based on solar PV and in 2014, the government implemented an auction to supply electricity through stand-alone solar PV systems to a minimum of 149,000 households and 2890 community buildings (Lucas et al., 2020). In Bolivia, according to the 2025 national plan for the electricity sector, universal access will require that 10% of the projects implemented in rural areas provide electricity service through off-grid renewable energy systems (Ministerio de Hidrocarburos & Energia, 2014).

Overall, analysis done for these countries can provide a positive learning curve for other developing countries with electricity access deficits.

Table 7.1 Comparison of electricity access rates and other development indicators associated with the selected countries (as of 2018). Source: Adapted from (IEA, 2019; INE, 2019; INEI, 2019; IRENA, 2020b; OPHI, 2018; UPME, 2019b; World Bank, 2018).

	Countries under Assessment		
Indicator	**Bolivia**	**Peru**	**Colombia**
Population (Million)	11.35	31.99	49.65
GDP per capita ($ US)	3548.59	6941.24	6667.79
Multidimensional Index Poverty (MPI) [a]	Value = 0.094	Value = 0.029	Value = 0.02
	H = 20.4%	H = 7.4%	H = 4.8%
	A = 46%	A = 39.6%	A = 40.6%
Rural population (%)	30.57	22.09	19.22
Access to electricity (%)			
Total (%)	92.8	92.9	96.5
Urban areas (%)	99.5	96.8	99.5
Rural areas [b] *(%)*	78.3	79.6	86.5
People without electricity access (Million)	0.9	1.2	1.7
Solar energy installed capacity (MW)	70	324	86
Universal electricity access target (year)	2025	2030	2030

[a] MPI = H·A where H is the proportion of multidimensionality poor people in the population and A is the intensity of poverty and reflects the average proportion of the weighted component indicators in which multidimensionality poor people are deprived. Estimation based on survey data: Colombia (2015/2016), Peru (2018), and Bolivia (2008). [b] Proportion of rural population with access to electricity.

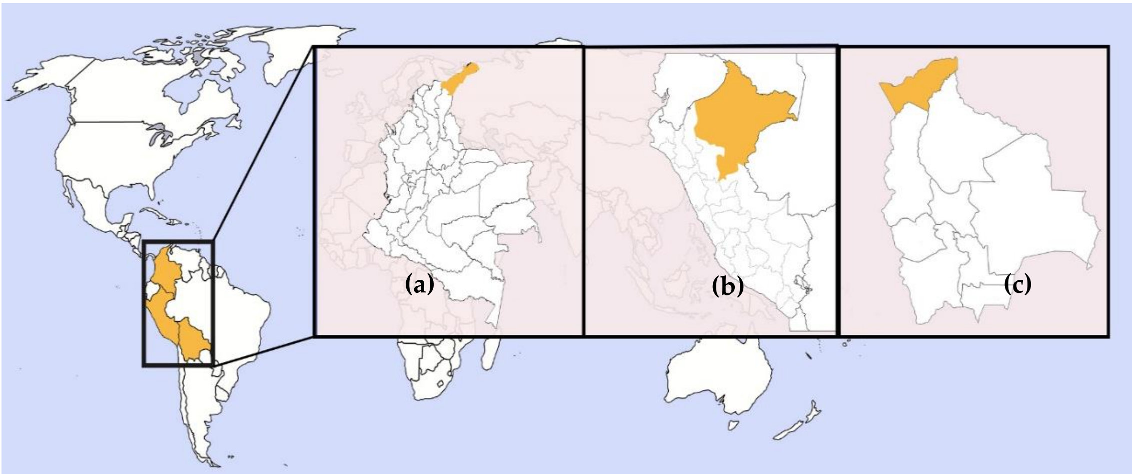


Figure 7.2 Off-grid location alternatives considered in this study: (**a**) Colombia, (**b**) Peru, and (**c**) Bolivia.

The technology energy solution to be implemented in each region correspond to standalone PV systems at the household level. Rural electrification programs within the selected countries are promoting the installation of this type of energy solution, since extending the grid to rural and remote areas is not an economically viable option (MEM, 2015; UPME (Colombia), 2018; VMEEA, 2014). In this case, it is considered a stand-alone system with a set of two (2) solar panels of 370 Wp each, a charge controller, a battery pack, an inverter, an electrical panel board, and the associated electrical installation, as illustrated in Figure 7.3.

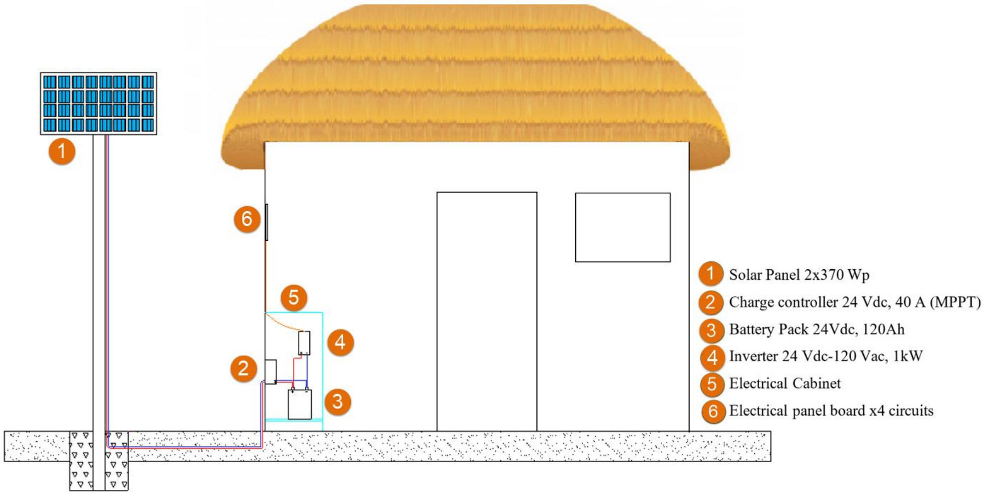


Figure 7.3 Off-grid solar PV configuration to be installed in each household.

After an interactive learning process, the model structuring began with the analyses of the DM's fundamental points of view (FPV). These are the relevant attributes used to evaluate each off-grid location alternative according to the DM's values. This approach is called "value-focused thinking" (Keeney, 1997).

These factors were identified by the DM based on his experience and they are related to the main issues to overcome and the type of risks the investors need to mitigate in order to guarantee the long-term sustainability of rural electrification projects (Schmidt et al., 2018). As a result, 13 evaluation criteria were grouped into five dimensions of sustainability: economic, commercial, technical, environmental, and social. Figure 7.4 provides an organised overview of these factors using a logical framework known as a "value-tree".

It is important to mention that despite being a highly interactive process, this chapter only presents here the outcome—the "requisite" model (Phillips, 1984). This means that several adaptations were necessary to guarantee that the form and content of the model were sufficient to provide satisfactory and undisputed answers to the DM's questions.

After pinpointing the fundamental criteria, the next step consisted of associating a measure (qualitative or quantitative) of the extent to which each criterion can be satisfied, namely a descriptor of performance that operationalises each criterion. According to Bana et al. (Bana et al., 2005), a descriptor of performance is an "ordered set of plausible impact levels or performance levels associated with an evaluation criterion". Considering the criteria underpinning this decision, it was opted to define quantitative descriptors to operationalise a criterion, where possible. Table 7.2 presents a brief description of each descriptor, its unit, and its relevance to the sustainability assessment of potential off-grid locations. This latter aspect reflects why it is important for the DM to consider each FPV and to what extent. The attractiveness of each potential location alternative, Bolivia, Colombia, and Peru is appraised by the DM within the corresponding performance scale. For instance, a higher priority is given to an area with a higher GDP because it gives the DM more confidence that the projects will be successful. A similar rationale is behind the concept of the other FPV: the alternatives having a lower poverty index, a higher financial inclusion, a greater number of households without electricity access, or a lower dispersion index are preferred.

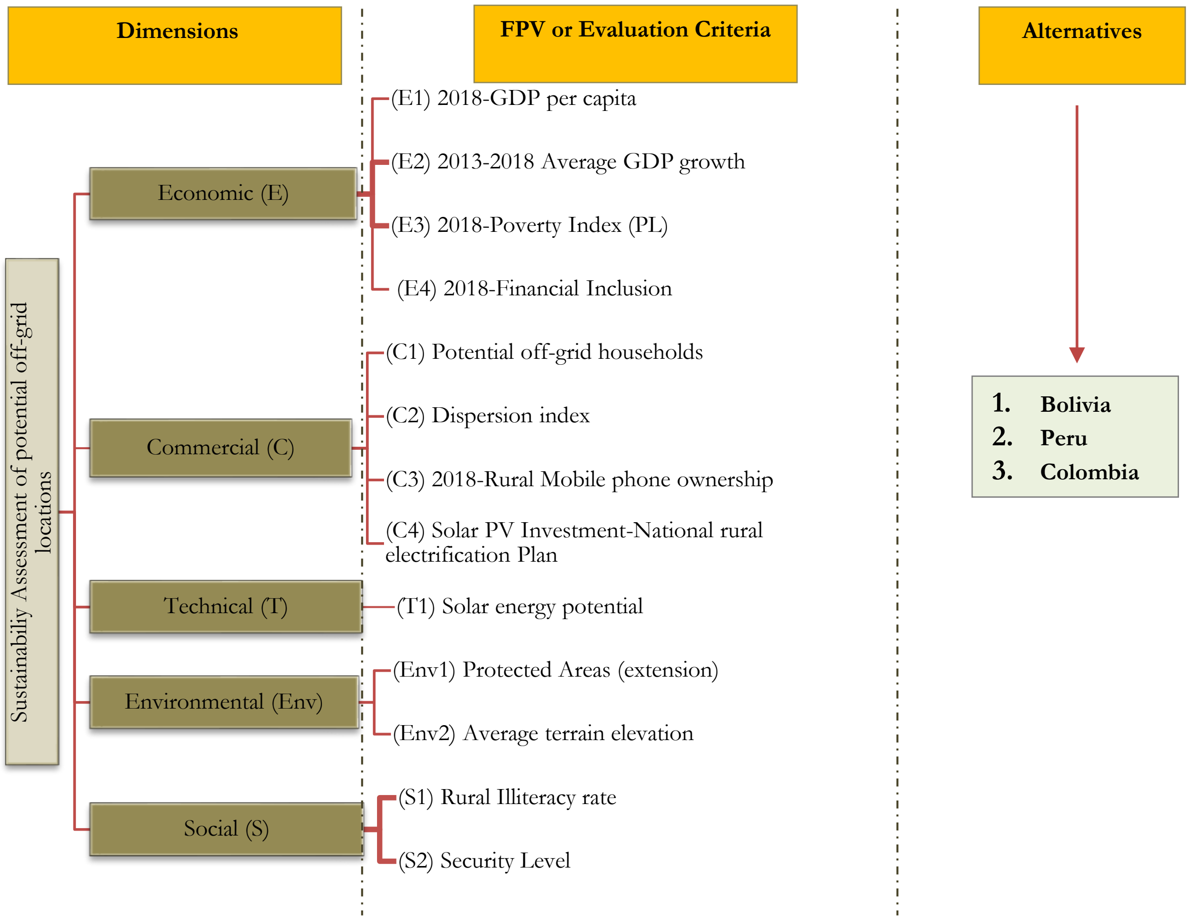


Figure 7.4 Final value tree of the evaluation criteria.

However, in this model, the potential off-grid locations presented different performances (the performance profile of each option is presented in Table B2 of the Appendix Section of this thesis) within the different evaluation criteria, thus, the process of choosing the option with the best performance was complex. If there had been an option that outperformed the others in every criterion, the choice would have been intuitive and there would have been no need to apply the M-MACBETH software to support the decision.

Table 7.2 Selected evaluation criteria and associated descriptors of performance. Source: Author's own elaboration based on (Fuso Nerini et al., 2014) and (Rahman et al., 2013)

Dimension	Criteria	Descriptors of Performance (Brief Description)	Unit of the Descriptor	Relevance
(E) Economic	(E1) 2018-GDP per capita	Estimated by the country's gross domestic product	US $	The extent to which a higher GDP provides more confidence about the economic performance of the country. This indicator allows for making cross-country comparisons of average living standards and economic well-being.
	(E2) 2013–2018 Average GDP growth	Estimated by the average of the GPD during the last five years	%	The extent to which the potential project is affected by the economic stability of the country. It reflects the country's efforts to promote economic growth.
	(E3) 2018-Poverty Index (PL)	Estimated by the percentage of people living in extreme poverty (currently set at $1.90 a day)	%	The extent to which the poverty condition of the families undermines the collection of payments and increases the customer churn rate.
	(E4) 2018-Financial Inclusion	Estimated by the percentage of people having access to at least one financial service (including bank account, credits, loan, equity, and insurance products)	%	The extent to which the potential project is affected by the lack of evidence of the consumer's credit history. It represents a risk to the energy provider who assumes the consumer's responsibility in repaying debts.
(C) Commercial	(C1) Potential off-grid households (without electricity access)	Estimated by the total number of potential households without access to electricity	Number of households	The extent to which the project is impacted by the new potential installations within a community. The higher the number of households, the better.
	(C2) Dispersion index (potential off-grid households/area)	Estimated by the population density of the potential site. In this case, the potential number of off-grid households per unit area	Number of households/km^2	The extent to which the project sustainability is affected by low-density communities, namely how scattered is the community within each potential region. This index increases/decreases the total installation and O&M costs of the project
	(C3) 2018-Rural Mobile phone ownership	Estimated by the percentage of people (>5 years old) living in rural areas, that own a cell phone	%	The extent to which the project's commercial operation is affected by the lack of local people owning a cell phone, required for the monetary transactions. It is important to guarantee the success of the energy prepaid model used by most off-grid energy companies.
	(C4) Solar PV Investment-National rural electrification plan	Estimated by the total investment for rural electrification projects based on solar PV energy and included in the National rural electrification plan	US $M	The extent to which the local government is investing in solar energy for rural electrification and in particular, if there are available funds to provide financing for solar PV projects in the country.
(T) Technical	(T1) Solar energy potential	Estimated by the Global Horizontal Irradiance (kWh/m^2). It is the total amount of shortwave terrestrial irradiance received by a surface horizontal to the ground	kWh/m^2	The extent to which the project is impacted by the availability of local solar energy resources. In rural and remote areas, having robust systems with high reliability is an important advantage due to the logistical difficulties in providing maintenance.
(Env) Environmental	(Env1) Protected Areas	Estimated by the percentage of conservation areas that receive protection because of their recognized natural, ecological, or cultural values	%	The extent to which the project is impacted by the percentage of protected areas (e.g., natural parks, indigenous settlements, or marine reserves), increasing/decreasing the installation and O&M costs of the project.
	(Env2) Average terrain elevation	Estimated by the altitude (above sea level) of the project's potential location	m.a.s.l.	The extent to which the commercial operation of the project is affected by the topography of the project location. It is measured by the easiness of accessing the community due to its terrain elevation.
(S) Social	(S1) Rural Illiteracy rate	Estimated by the percentage of the population (>15 years old) that can read and write	%	The extent to which the commercial operation of the project is affected by the lack of local technicians with a minimum level of education. Hiring local technicians not only reduces the installation and O&M costs but also increases community acceptance.
	(S2) Security Level	Estimated by the Global Peace Index which measures the level of peacefulness within a country	points	The extent to which the potential location provides a good level of safety for the technical staff installing/operating the systems in the community. Some indicators included in this score are the number and duration of internal conflicts, and the number of homicides per 100,000 people, among others.

7.1.1.2. Building the Additive Evaluation Model

After the classification of the options according to each FPV, the next step was the construction of the multi-criteria additive evaluation model. Following the MACBETH approach, the value functions for each FPV were built. This process was done by requesting the DM to define two reference levels (or anchors) in terms of performance for each FPV: a reference of "Neutral" performance and a reference of "Good" performance, explaining that the former refers to the level below which there are the unattractive options or from which the DM set a minimally satisfying performance and the latter refers to the level above which there are the most attractive or outstanding options with satisfying performance. The partial values (v_j) of these anchors for a criterion j are defined as: $v_j(good) = 100$ and $v_j(neutral) = 0$. These references helped us to investigate whether each option had an undesirable (worse than Neutral), satisfactory (from Neutral to Good), or outstanding (better than Good) performance (Hummel et al., 2017). As a result, Table 3 presents the reference levels for each descriptor.

Table 7.3 Reference levels ('good' and 'neutral') and attractiveness of each criterion.

Dimension	Criteria	Reference Values		Ranking of Importance
		Neutral (Acceptable)	**Good**	
Economic	(E1) 2018-GDP per capita	5000	6000	4
	(E2) 2013–2018 Average GDP growth- 5 years	3	7	3
	(E3) 2018 Poverty Index (PL)	30	20	5
	(E4) 2018 Financial Inclusion	60	80	8
Commercial	(C1) Potential off-grid households (without electricity access)	40,000	80,000	1
	(C2) Dispersion index (potential off-grid households/area)	0.5	1	2
	(C3) 2018 Rural Mobile phone ownership	50	60	6
	(C4) Solar PV Investment-National rural electrification plan	200M	400M	9
Technical	(T1) Solar potential	Medium	Very High	11
Environmental	(Env1) Protected Areas	10	0	12
	(Env2) Average terrain elevation	110	50	13
Social	(S1) Rural Illiteracy rate	10	5	7
	(S2) Security Level	4	0	10

Afterwards, to build the value functions for each FPV, the DM was requested to give a qualitative judgement on the difference in attractiveness between levels of performance of the respective FPV. To model the differences in preference, the DM used one of the seven MACBETH categories for the judgements, namely: "extreme", "very strong", "strong", "moderate", "weak", "very weak", and "no" difference. If unsure about the difference in attractiveness, the DM could choose more than one qualitative rating. If any two options were considered to be equally attractive during the ranking process, they were assigned a "no" in the matrix (Bana e Costa et al., 2012). Then, after checking for no remaining inconsistencies, these judgements were processed by the M-MACBETH and the program proposed a quantitative value function for each FPV (See Figure B1 of the Supplementary Material). This quantitative value function represents the judgements of the DM and assigns value scores to the levels of each performance descriptor relative to the fixed scores of 0 and 100 (i.e., the neutral and good reference levels in the model). As a simplification (and to expedite the decision meetings), this model assumes a linear relationship between performance and score, namely a linear value function that measures the attractiveness of each site alternative within each FPV (Bana e Costa et al., 2008). This additive aggregation is represented by the value function model defined in Equation 7.1:

$$V(x_i)=\sum_{j=1}^{n} w_j v_j(x_i), \qquad \text{Equation (7.1)}$$

With,

$$\sum_{j=1}^{n} w_j = 1$$

$w_j>0$

$v_j(x_i^+)=v_j(\text{'good'}_i)=100$

$v_j(x_i^0)=v_j(\text{'neutral'}_i)=0$

$i=1,\ldots,m$ and $j=1,\ldots,n$

where $i=1,\ldots,m$ represents each site alternative and $j=1,\ldots,n$ designates each evaluation criterion (e.g., Dispersion Index); w_j are the scaling constants or the weighting coefficient assigned to criterion j multiplied by the partial value score $v_j(x_i)$; x_i^0 and (x_i^+) are, respectively, the neutral and good performance levels defined for each performance descriptor, and $V(x_i)$ is the overall score of alternative x_i that measures its global attractiveness. As a result, the most appropriate off-grid location results from max V in Equation 7.1.

7.1.1.3. Computing the Weighting Coefficients

In order to measure the added benefit of each potential off-grid location, the weighting coefficients of each criterion were defined. According to Marques et al. (Marques et al., 2015), weighting coefficients are 'scaling constants' that transform partial scores (in each criterion) into global scores. For each criterion, these coefficients represent the importance that the DM gives to the swings in performance (e.g., from 'neutral' to 'good'). Thus, after establishing how well each off-grid site alternative performs on each criterion, those performances must be combined or aggregated to have an overall score for each potential site. This stage of the model evaluation consisted of ranking the criteria by decreasing the order of attractiveness, considering a switch from "neutral" to "good" reference level of each criterion. For this purpose, this study applied the MACBETH qualitative swing weighting process (Bana e Costa and Chagas, 2002), and the following question was asked: "Presume that one of the alternatives is expected to have a low ('Neutral') performance on all 13 criteria; on which criterion would a swing from 'Neutral' to 'Good' be most attractive?" The same question was made for the second most important criterion, and so on until the last criterion was included. The final ranking is presented in Table 7.3. Then, the DM compared qualitatively the most important swing to each of the others and finally, followed by the comparison of each two swings consecutive in the ranking.

As each DM's judgement was given, the M-MACBETH software automatically verified the matrix consistency and suggested judgements modifications that were used to fix the detected inconsistencies. Finally, the software proposed a set of weighting coefficients that were compatible with the DM's qualitative judgements. With these weights and the partial value function $v_j(x_i)$ of each option for each criterion, the software also computed the global attractiveness of each option. This overall score resulted from the additive aggregation of the weights and performance of each option within each criterion, as defined in Equation (7.1).

7.1.1.4. Testing the "Requisiteness" of the Model

As presented in Figure 7.1, the last step of the multi-criteria modelling consists of validating the model. This process required performing a sensitivity analysis. Thus, some susceptibilities and assessed the model's consistency were modelled. In particular, the study evaluated how a change in any of the weights (within the allowed interval) would affect the overall scores of the options, and, to a greater extent, possibly change the model's recommendation. To facilitate this process, first, the DM was asked to examine and confirm the weights and then to identify the weights whose values he was not certain about. Finally, the effect on the alternatives' overall score was validated and analysed.

7.2. Results and Discussion

In this study, a multi-criteria decision analysis approach was applied, namely, an additive value model, to evaluate the performance of three potential site options for implementing an off-grid solar PV project. By using the MACBETH approach and software, it was possible to have an overview of the performance profiles of the assessed options, rank each site alternative according to a sustainability scale, identify the main factors influencing the site selection process, and show the remaining challenges that investors and policymakers need to overcome to guarantee the sustainability of off-grid solar PV projects in developing countries. This section presents the main results of the implemented sustainability assessment process. These results only represent one type of stakeholder, namely the private sector or developers of off-grid solar PV projects.

Based on the weighting procedure above mentioned, the DM ranked the criteria, and with his qualitative judgements, the M-MACBETH software provided the numerical weights for each criterion, as illustrated in Table 7.4.

Table 7.4 Weights of criteria and associated dimension.

Dimension	Weight (%)	Criteria	Weight of Criteria (%)
Economic	42.16	(E1) 2018-GDP per capita	12.71
		(E2) 2013–2018 Average GDP growth- 5 years	12.71
		(E3) 2018 Poverty Index (PL)	11.52
		(E4) 2018 Financial Inclusion	5.22
Commercial	45.75	(C1) Potential off-grid households (without electricity access)	18.47
		(C2) Dispersion index (potential off-grid households/area)	16.52
		(C3) 2018 Rural Mobile phone ownership	8.91
		(C4) Solar PV Investment- National rural electrification plan	1.85
Technical	1.2	(T1) Solar energy potential	1.2
Environmental	1.53	(Env1) Protected Areas	0.87
		(Env2) Average terrain elevation	0.66
Social	9.36	(S1) Rural Illiteracy rate	7.83
		(S2) Security Level	1.53

The obtained weights have a direct influence on the final decision because they allow the DM to evaluate the most critical dimension and criterion affecting the selection of an off-grid market. The resulting matrix of judgements is presented in Table B4 of the Appendix section of this thesis.

Accordingly, the sum of each criterion yielded the total weight assigned to each dimension. Overall, the *Economic* and *Commercial* dimensions report the highest importance compared to the other dimensions: 45.75% and 42.16%, respectively. In contrast, the *Technical* dimension has the lowest effect on the final decision, weighing 1.20%. This result suggests that the *Solar energy potential* criterion was not considered a determinant factor to have a preferred option, mainly because the three site options exhibit a similar performance, having a very high potential (i.e., GHI > 4.5 kWh/m^2) (The performance profile of each option is included in Table B2 of the Appendix Section of this thesis). Thus, none of the options outperforms the others in this criterion. Figure 5 shows the relative weights for each criterion within the five dimensions. The *Potential off-grid households* and the *Dispersion index* represent the criteria with the highest importance compared to the other key factors: 18.47% and 16.52%, respectively. This result evidences the importance of the project size (i.e., the number of households without electricity access) not only to guarantee financial viability but to prioritise the communities where the project could impact more lives. This value refers to the number of new connections that the company should make to meet its costs, that is, to break even and, according to the DM, it has a value between 5,000 and 8,000.

Regarding the *Dispersion index*, it was considered the second most influencing criterion, because the installation of the systems and the associated installation and O&M costs depend on how scattered the potential community within each potential region is.

Figure 7.5 also evidences that the *Protected areas (%)* and the *Average terrain elevation (m.a.s.l.)* criteria have the lowest weights in the selection of an off-grid market: *0.87%* and *0.66%*, respectively. In this respect, it was clear that rural electrification investments must acknowledge the special geographic conditions of the regions where off-grid communities are usually settled. Therefore, an additional margin on the operation and maintenance costs is often included to cover the expenses of projects exhibiting logistical constraints. As a result, the obtained weights for these criteria suggest that no matter the off-grid project location, investors must cope with the local environmental constraints, and thus, for this particular case, these two criteria have no determinant influence (both weights sum up to 1.53%) on the final selection of the potential site.

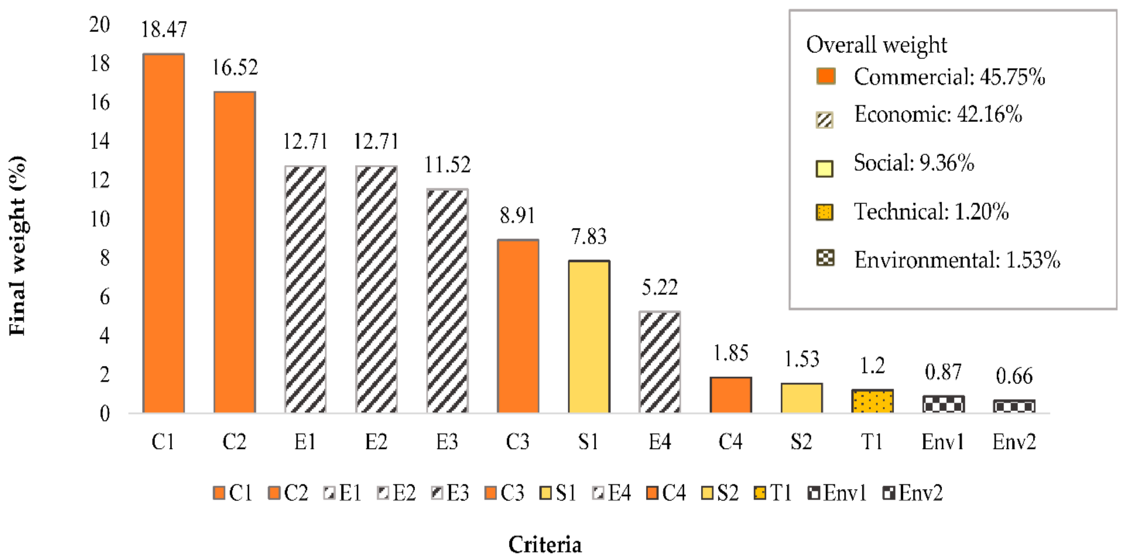


Figure 7.5 Weights for each criterion (by decreasing order) and associated dimension according to the DM's preferences.

Having the relative weights for each criterion, it was possible to determine the associated sustainability assessment score for each option (i.e., La Guajira (Colombia), Loreto (Peru), and Pando (Bolivia)), across all the dimensions and criteria. In particular, Figure 7.6 presents the scores associated with each dimension by country. These scores represent the degree to which each dimension contributes to each option's sustainability.

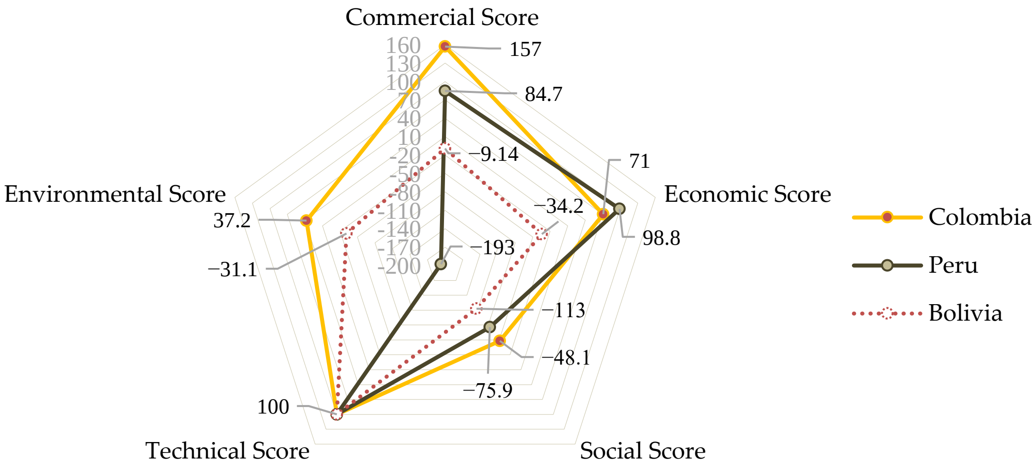


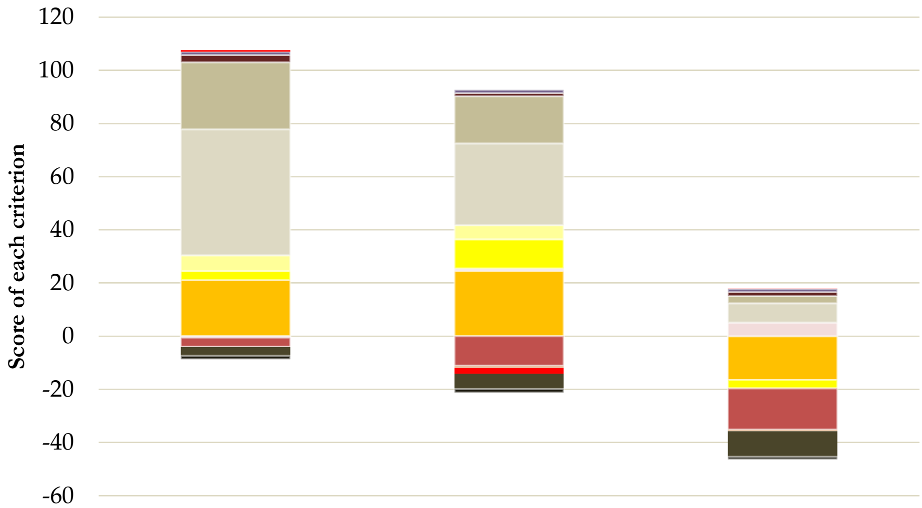
Figure 7.6 Radar chart presenting the decomposition of each dimension score for each country.

As presented in Figure 7.6, Colombia has the best performance in terms of the Commercial, Environmental, and Social dimensions, which have a direct influence on the site selection at about 57%, whereas Peru has a better performance in the Economic dimension. Figure 7.6 also shows that the Commercial, Economic, and Environmental dimensions are determining factors between the worst options, making Bolivia less attractive than Peru.

Additionally, in order to provide a more structured approach to evaluating the prospective potential market, another question was addressed: "what are the biggest differences between the options, in terms of the criteria?" As a result, all the criteria were evaluated individually for each of the potential regions. reports the final values of the aggregate scores associated with each criterion, based on a 0 (neutral) and 100 (good) scale of reference.

Figure 7.7 displays more clearly the biggest differences between the positive and negative scores across the options. In particular, it reveals why Colombia has a better overall score. Also, it shows that Colombia and Peru are mainly positively scored options and most of the criteria are weighted above neutral, especially in Colombia. By paralleling the scores of Colombia and Peru (the two best options), results reveal that Colombia has a better performance in terms of the *Potential off-grid households* and the *Dispersion Index*, a similar performance for *GDP per capita*, *Solar potential*, and *Security level.* The only downside for Colombia is the *Average GDP growth* that is below the neutral score, representing a low increase in economic performance compared to *Peru* and *Bolivia.*

The *Rural Illiteracy rate* criterion is a common punishing factor between options, which shows the low potential of finding skilled personnel in the three regions. Also, the *Dispersion Index* has another negative effect on the global score. These two FPV have an impact weight of 7.83% (*Rural Illiteracy rate*) and 16.52% (*Dispersion*) and they will be evaluated in the sensitivity analysis.



	Colombia	Peru	Bolivia
S2	−1.24	**−1.34**	**−1.05**
S1	**−3.26**	−5.76	**−9.52**
Env2	**0.66**	**−2.2**	0.18
Env1	**−0.09**	**−0.75**	−0.65
T1	**1.2**	**1.2**	**1.2**
C4	**1.97**	**1.19**	1.45
C3	**25.25**	17.82	**2.76**
C2	**−3.58**	−11.12	**−15.58**
C1	**47.4**	30.86	**7.19**
E4	**5.74**	5.22	**0**
E3	3.46	**10.94**	**−3.04**
E2	**−0.48**	0.83	**5.15**
E1	21.2	**24.67**	**−16.54**

Figure 7.7 Decomposition of each criterion score by country option. Note: Highest criteria score in **green**, lowest in **red**.

On the other hand, by comparing Bolivia and Peru, it was noticed that Bolivia only has six positive weighted criteria (i.e., values in *Average Terrain Elevation (Env2), Solar Potential (T1), Solar PV investment (C4), Mobile phone ownership (C3), Potential off-grid households (C1)* and *Average GDP growth (E2))*. In particular, the *GDP per capita* criterion with an overall weight of 12.71% (see Figure 5) has the worst effect on Bolivia's global score, representing an entry barrier and a less appealing option for the DM. As previously illustrated in the value tree shown in Figure 7.4, there are five primary dimensions for the off-grid site selection problem. Looking at the results, it was clear that Colombia was the best option in terms of the Commercial, Environmental, and Social dimensions. However, there were some divergences in the Economic dimension with Peru having a better performance in this respect. Figure 7.8 presents an XY map to compare the options' scores in a bi-dimensional graph between two criteria or dimensions. In this case, the line that connects the options maximizes the score for the Economic dimension. The previous analysis showed that although there were three options, only two of them had positive overall results, so it was expected that the efficient frontier only took Colombia and Peru into account. As mentioned earlier, the weight of the Economic dimension is 42.16% (12.71% from *GDP per capita,* 12.71% from *Average GDP growth,* 11.52% from *Poverty Index,* and 5.22% from *Financial Inclusion*). This result was used as a starting point for sensitivity analysis of the best two options found.

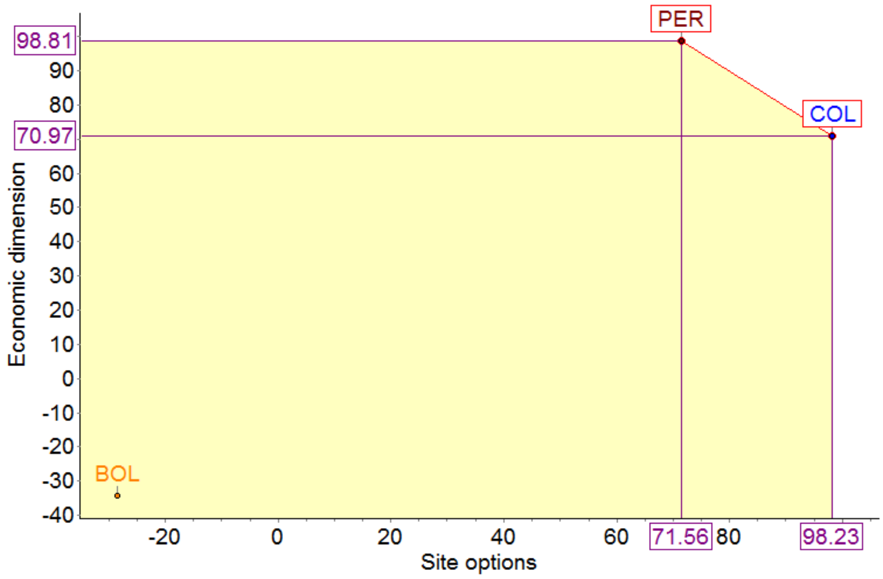


Figure 7.8 XY Map-Site selection vs. Economic dimension. Source: Retrieved from MACBETH software.

On the other hand, the application of the model enabled the DM to appraise the potential alternatives under consideration. After considering the scores for each criterion and the associated weights, the model proposed Colombia as the most attractive option given the DM's judgements. This country has the best score (98.23 on a scale of 0 to 100), leading Peru (the second-best option) by about 27 points.

Based on the sustainability score attained by each country and also on the definition used to set the good and neutral levels of reference associated with each criterion, the countries' sustainability was categorised as follows (Marques et al., 2015):

- Highly sustainable: if the potential site has a score above 100 (i.e., more sustainable than a country that has a performance equal to the 'good' level in all criteria).
- Sustainable: if the potential site has a score between 0 and 100 (i.e., it represents the minimum acceptable level)
- Unsustainable: if the potential site has a score below 0 (i.e., less sustainable than a country that has a performance equal to the 'neutral' level in all criteria).

As presented in Table 7.5, the off-grid solar PV project in La Guajira, Colombia, has the best performance in the sustainability assessment, namely, it represents the highest sustainable option for a project investor, among the remaining site options. Table 5 also shows that not all the alternatives have a positive evaluation score, which suggests that Bolivia is a low viability alternative or an unsustainable option for the DM, with a score of −28.56. None of the options has a highly sustainable score, meaning that none of the countries represents an outstanding option, however, Colombia and Peru, are the alternatives with a minimally satisfying performance according to the DM's judgements of preference.

Table 7.5 Global Scores for the most appropriate market option and the associated level of sustainability.

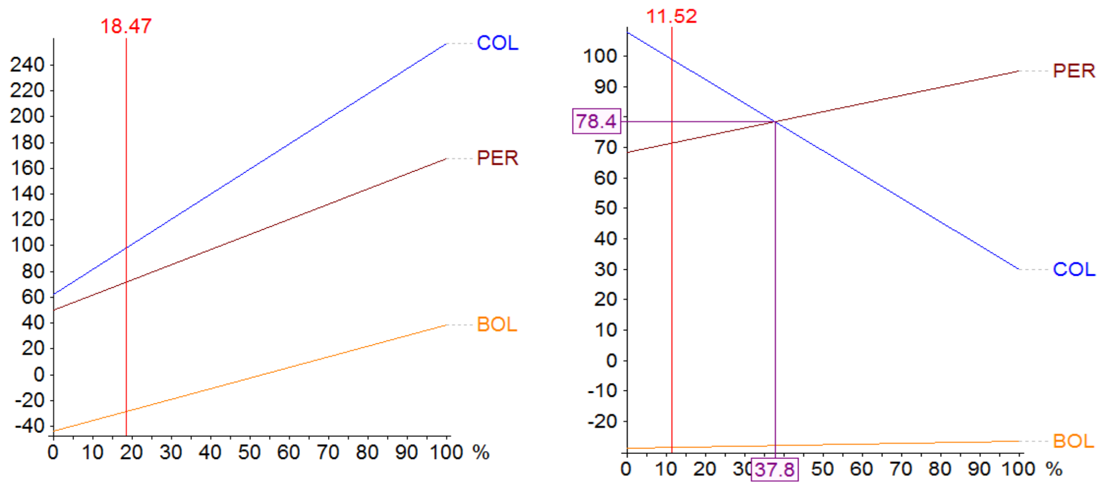
Market option	Global Score of Appropriateness *	Country Sustainability
Colombia	98.23	*Sustainable*
Peru	71.56	*Sustainable*
Bolivia	−28.46	*Unsustainable*

* The larger the score, the most appropriate the site, based on a 0 (neutral) and 100 (good) scale of reference.

7.2.1. Sensitivity Analysis

A sensitivity analysis was also performed to validate the consistency of these outcomes. The purpose of sensitivity analysis is to refine the decision model, with the ultimate objective of obtaining a requisite model, which when subjected to sensitivity analysis, yields no new intuitions (Phillips, 1984). There are several types and tools of sensitivity analysis. Simple one-way sensitivity graphs can be carried out using tornado diagrams and spider graphs. Also, sensitivity analysis simultaneously accounting for many variables can be done using Monte Carlo simulation models. This study uses the M-MACBETH software to assess the consistency of the final ranking of the countries' alternatives.

The model was tested using two scenarios and the susceptibility of the overall score of the options was studied, by making small variations of one criterion weight at a time. This analysis was performed on the positive overall scored options (Colombia and Peru). Figure 7.9 shows the modifications that occur from modifying the weight of a criterion while maintaining the proportion between the remaining criteria weights. Figure 9a shows that the model's result is not sensitive to variations in the weight of the *Potential off-grid households*. This means that the relative global scores of the countries' alternatives remain unmodified, and Colombia continues to be the most sustainable option. This is relevant when considering that this criterion has the highest influence in the evaluation model, i.e., the highest weight (18.47%).



(**a**) (**b**)

Figure 7.9 Sensitivity analysis on weight for criterion: (**a**) Potential off-grid households; (**b**) Poverty Index. Source: Retrieved from M-MACBETH software.

As previously perceived, Colombia is always preferable to Peru in terms of the Commercial, Environmental, and Social dimensions, but in terms of the Economic dimension, there were some doubts about the sensitivity of the weight obtained. In this dimension, Colombia had similar behaviour in the following criteria: *GDP per capita, Average GDP growth,* and *Financial Inclusion,* compared to Peru. Figure 9b shows the Economic dimension susceptibility in terms of the *Poverty*

Index. When increasing the weight of this criterion from 11.52% to 37.8%, the final overall relative score changes and the model proposes Peru as the most attractive alternative. However, this is less likely to occur since there are other economic important criteria to consider in the decision-making process, such as the *GDP per capita,* and the *Average GDP growth* representing a total weight of 25.42% on the final selection.

Both situations were validated with the DM and no change in weights was required. It is worth mentioning that in terms of the Commercial, Environmental, and Social dimensions, both countries had divergent scores for the set of criteria, so no matter the weight, Colombia is always the most suitable site option.

There are two possible areas for further work. First, this study proposes to validate the obtained set of criteria, by calibrating this model with the input of other decision-makers (e.g., other off-grid energy utilities, actors from the local government, and experts from the academic sector) to reflect a diversity of stakeholder views. Second, this study suggests including additional factors that were not considered in this study, namely the following criteria: *Community acceptance* (i.e., to guarantee the successful implementation of an off-grid system, the project should fit well into the socio-cultural context of the community) and *Political environment* (i.e., the extent to which the potential business is impacted by the political stability of the country), which could also contribute to the long-term sustainability of off-grid projects. Finally, it would be useful to provide a detailed discussion of how to make those regions not selected, more attractive to investors.

7.3. Chapter Summary

In this chapter, a multicriteria model was implemented to support a decision-maker representing the private sector's point of view, in evaluating the performance of three off-grid site alternatives against 13 criteria grouped in 5 sustainability dimensions.

In summary, the main contribution is threefold: first, results provide a useful roadmap for MCDM modelling through participatory processes, with a practical example of how to structure a model considering the case of developing countries, and in particular, the context of off-grid rural electrification projects. Second, it identified key criteria and associated descriptors of performances that contribute to achieving sustainability in the off-grid energy sector. This study integrated two additional sustainability dimensions to the TBL approach, namely the technical and commercial criteria. These additional dimensions build upon the technical and non-technical features that influence the decision-making of selecting the most appropriate off-grid site to implement solar PV projects, based on the private sector's point of view. Third, our general findings may offer some direction for project developers and potential investors willing to undertake their sustainability assessments. This methodology can be applied to evaluate other regions, namely, to identify and prioritise geographical areas for the provision of electricity access.

This analysis can be replicated to assess other potential off-grid locations and thus, roll out electricity access programs in developing countries.

8. Unlocking private investments in the off-grid electrification sector

This chapter focuses on the economic and policy dimensions of the sustainable planning framework proposed in this thesis. One of the key factors towards achieving universal access is enabling private investments in the rural electrification sector, as public resources are scarce. However, off-grid electrification projects are often considered high-risk investments by utilities and off-grid service providers, mainly due to the uncertainty around revenues, project sustainability, and potentially low returns. In consequence, potential investors face the decision problem of deciding where to invest in rural and remote areas, while measuring the attractiveness of a project by its expected financial return and its associated risks. This chapter identifies the key uncertainties and perceived risks arising in the off-grid rural electrification sector, based on the literature review and the private sector's point of view while using a stochastic discount cash flow technique — net present value (NPV) combined with Monte Carlo simulation — to incorporate these uncertainties and quantify the business and investment risks associated with an off-grid solar PV project. The technique is applied to the case of Colombia, wherein major contributors to risk are the variability in revenues and the annual revenue growth rate.

Chapter 5 presented a general overview of the main public financing mechanisms set by the GoC to expand electricity access in the most rural and remote areas of the country. As highlighted in these chapters, public interventions are not enough to achieve universal access by 2030, and thus, additional investments from the private sector are required not only to accelerate the provision of reliable electricity access but to unlock opportunities for renewable electricity development in Colombia's ZNI and to enable the necessary capital flows for those solutions.

It is necessary to enable different support mechanisms and potential financing instruments that can be used to encourage investment in off-grid renewable electricity, looking in particular at strategies to crowd-in private finance, including de-risking tools and financing instruments that maximise the use of public and development funds.

Overall, the lack of private investments in the off-grid sector of Colombia is confirmed by considering the number of energy service providers (i.e. with administration, operation, and maintenance activities in the ZNI. As of December 2020, more than 50% of the registered operators (94 in total) were public entities (See Figure 8.1) (CNM, 2020). The other operators corresponded to private or mixed capital companies with limited liability, including local community cooperatives, exclusive service areas (ASE in Spanish), and off-grid energy service companies (ESCO) (IDB, 2016). One of the main reasons for having this low private sector participation is that companies willing to provide O&M activities in these areas face high costs that cannot be recovered through the tariff and the subsidy scheme. The electricity costs in the ZNI are very high compared to the costs in the SIN (around US$0.26/kWh compared to US$0.11/kWh, respectively), mainly due to local constraints that hinder the provision of the electricity service. Some of these aspects are related to the dispersion of the communities, the geographic location of the projects, and the lack of local skilled personnel or local inappropriate infrastructure (i.e. lack of paved roads, water service, and mobile phone network).

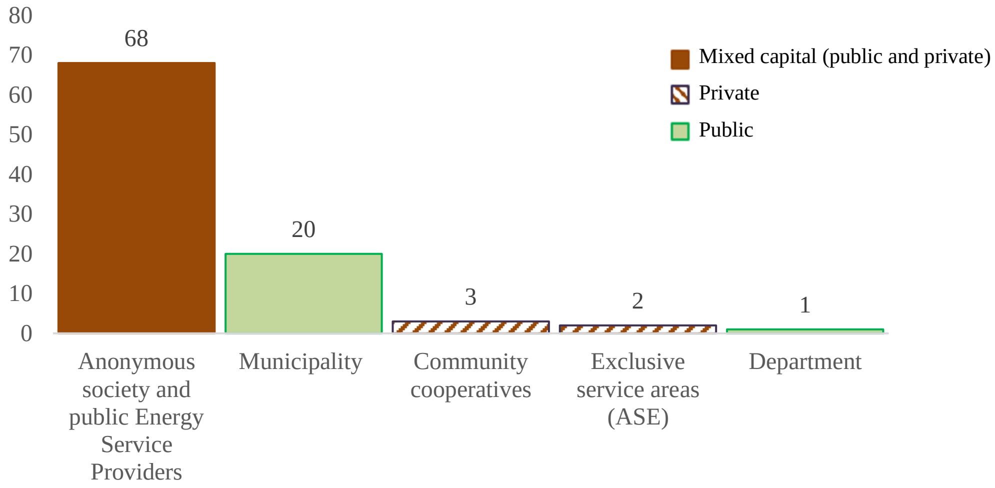


Figure 8.1 Type of energy service provider. Source: (CNM-IPSE, 2021)

8.1. Predominant business models in the ZNI

The predominant business model in the ZNI has relied on the intervention and financing of public entities. Traditionally, electrification projects have been approved by the FAZNI committee, through two schemes, as it is set in the Decree 1124 of 2008 (MME, 2008): 1) As a result of public invitations designed by the MME, for infrastructure investment projects in non-interconnected areas, and 2) On the initiative of local authorities (e.g. local municipalities' mayors, departments or ethnic communities that have the endorsement of the territorial entity), and the IPSE (See Figure 8.2). The FAZNI provides 100% capital investment to selected projects (i.e. following a prioritisation methodology) that have received technical feasibility by the IPSE, to cover equipment costs, engineering, construction, legal and contractor fees, and the households' electrical installations in the ZNI. Under this scheme, the MME owns 100% of the assets and granted service providers acquire the compromise to respond to the operation and maintenance of the infrastructure, under a Build, Operate, Maintain and Transfer (BOMT) contract of about 5 to 10 years (IDB, 2016) (See Fig). Regarding operating expenses (OPEX), the GoC covers a percentage of these costs with the regulated tariff and a monthly subsidy provided to end-users through FSSRI.

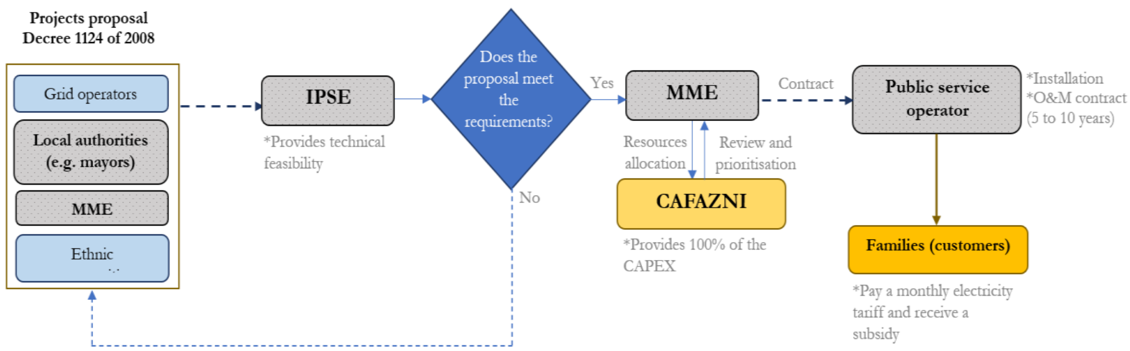


Figure 8.2 Traditional business model in the ZNI under the FAZNI. Source: Author's own

8.2. Study area

The Colombian context was considered to quantify the main uncertainties and perceived risks by private investors willing to implement off-grid solar projects with stand-alone PV systems. There are three reasons to focus on the Colombian case study: First, the government of Colombia (GoC) aims to achieve universal access by 2030 (UPME, 2019a). Second, national electrification programs and plans are promoting RE decentralised solutions to expand electricity access in rural and remote areas, where extending the grid is not an economic option. According to Colombia's electricity coverage expansion plan (PIEC 2019-2023), increasing the current electrification rate from 96.5% to 100% by 2030 requires that 91% of the up-front required investment or €1.7 billion focuses on providing electricity access either through hybrid minigrids or through stand-alone PV systems whilst 9% of the investments are derived to grid extension projects (UPME, 2019a). Third, historically, private investment in RE off-grid projects has been low (less than 10%) and more than 50% of the service providers in the off-grid areas of Colombia (94 in total) correspond to public entities (CNM-IPSE, 2021).

In specific, the Tumaco municipality is considered. It is located in the Narino department (See Figure 8.3), which corresponds to one of the five regions of the country with the highest electricity access deficits (UPME, 2019a). This analysis considers the case of a local project financed through the financial support fund for the electrification of the ZNI (FAZNI) where nearly 890 stand-alone PV systems were installed between 2020 and 2021(CREG, 2020a). This public fund provides a 100% subsidy on the CAPEX of the system, including the installation of the following components: a set of two (2) solar panels of 370 Wp each, an inverter of 1 kW, a battery pack of 120 Ah, a charge controller of 40 A, an electrical panel board of four (4) circuits, and the wiring system required for the electrical installation of three (3) domestic electrical sockets and two (2) light bulbs (MME, 2020b).

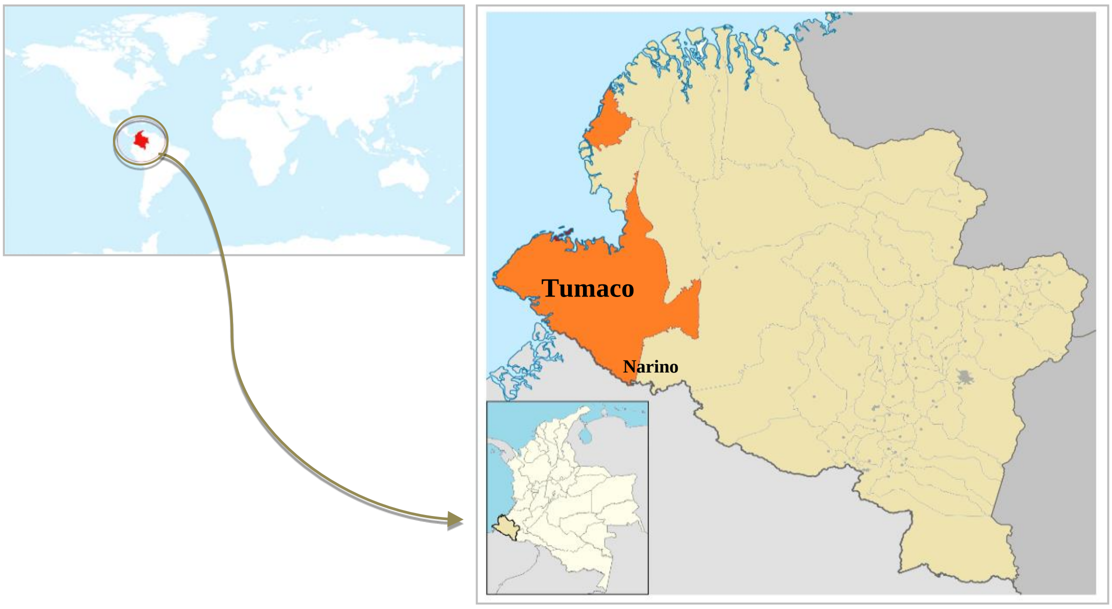


Figure 8.3 Location of the selected solar PV off-grid project in Colombia. Source: Authors' own

8.3. Results and discussion

Results are mainly derived from the literature review and semi-structured interviews involving three experts in energy planning and rural electrification projects, from EDPDistribuição[3], EDPAccess2Energy[4], and IPSE[5] (*personal communication, June 2019 and January 2022*).

[3] EDP (Energias de Portugal) is a major electricity distribution utility serving most of the regions in Portugal

[4] Access2Energy (A2E) is an EDP's fund program is aimed to reduce energy poverty by supporting sustainable and clean energy projects in developing countries

[5] IPSE (Institute for the Planning and Promotion of Energy Solutions in the non-interconnected zones) identifies, promotes, structures, implements, and monitors sustainable energy solutions in the ZNI.

Four types of uncertainties were categorised into three risk categories: business, investment, and financing risks, based on the literature review and the semi-structured interviews. Table 8.1 shows the perceived uncertainties and resulting risks that require deeper analysis from potential private investors in the off-grid electrification sector of Colombia.

Table 8.1 Perceived uncertainties and resulting type risk. Source: Authors 'own from Literature review and semi-structured interviews, (Bekker, 2010; Schmidt et al., 2018)

Uncertainty	**Source of Uncertainty**	**Perceived risk *(Brief description)***	**Risk Category ***		
			B	**I**	**F**
Revenues	Electricity Tariff	• R1. The company is not able to recover its costs through the monthly tariff since the currently regulated electricity tariff does not provide enough revenue.	●		
	Access to Subsidies	• R2. Decrease in the company's revenues because subsidies are not enough to recover the costs of the projects.	●		
	Ability and willingness to pay	• R3. The customers' ability and willingness to pay for the service affects the financial sustainability of the project. Investors need to account for the fact that customers living in rural areas have lower incomes than their counterparts in cities.	●		
	Energy demand	• R4. Decreased revenues (i.e. electricity sales) because electricity sales are lower than expected. This risk comes primarily from the uncertainty about the community energy demand or the level of energy demand in each household.	●		
	Community acceptance/ awareness	• R5. The project does not provide enough revenue. If the community is found unsupportive, the system may face many local challenges such as thieving, damaging, tampering, etc., which affect the company's revenues.	●		
	Customer churn rate	• R6. Decrease in the company's revenues due to an increasing percentage of customers discontinuing their subscriptions within a given period.	●		
Operating Costs	Cost structure	• R7. Project failure and/or increase disinterest of private investors to entry in the off-grid electrification market. This risk is associated with the uncertainty regarding the definition of how much of the operating cost is fixed cost and how much is variable cost (See Section 4.1.1.)	●		
	Number of technical visits	• R8. Increased operating costs since there is no certainty about the number of technical visits required to provide preventive maintenance within the community, which could increase the operating costs (i.e. expenses for maintenance of the systems, salaries, transportation, rents, etc.)	●		
	Technical failure of components	• R9. Higher operating costs are derived from an increased number of maintenance visits. This risk comes primarily from the uncertainty about the failure of the off-grid electrification system due to factors like component reliability, lightning damage, and system design and configuration (See (Bekker, 2010)).	●		
	Lack of raw materials and skilled labour (O&M)	• R10. High operating expenses are derived from a lack of local skilled and qualified potential employees and a lack of raw materials.	●		
		• R11. Project failure because the community is not willing to accept foreign manpower (i.e. technicians) for the project implementation	●		
	Theft of components/sy stem	• R12. Higher operating costs because the investor assumes the system replacement when theft and vandalism occur. This aspect is related to the lack of customer ownership. The link between ownership and theft is widely acknowledged in literature (See (Bekker, 2010)).	●		
Investment	Sources of capital investment	• R13. Low private sector participation in off-grid electrification projects because there is a lack of financing funds providing capital investment.		●	
Financing scheme	Higher levels of debt	• R14. Business failure and bankruptcy because the investor is unable to meet its interest payments to avoid. Higher levels of debt generally make the company riskier.			●
	Changes in interest rate	• R15. The company is unable to meet its debt commitments for projects partly funded with debt due to changes in interest rates. The lenders expect the interest payments on the debt irrespective of the conditions under which the business is operating (i.e. The variability in the interest rate).			●
	Incentives provided by the government	• R16. Low private sector participation in off-grid electrification projects due to a lack of a well-defined incentive scheme (e.g., tax incentives, VAT exemption, etc.) to reduce costs and provide legal security.			●

*"B", "I", and "F" stand for Business, Investment, and Financing risks, respectively.

Table 8.1 shows that 12 out of the 16 types of potential risks correspond to Business Risks, which refers to the variability of the company's anticipated earnings from normal operations. Figure 8.4 presents the resulting Risk Map which summarises the results of the risk identification and assessment process. It provides a comparison of the perceived project risks identified in Table 8.1. Each of the 16 potential risks was rated on two dimensions: the probability that a risk will occur is represented on one axis and the impact of the risk, if it occurs, on the other.

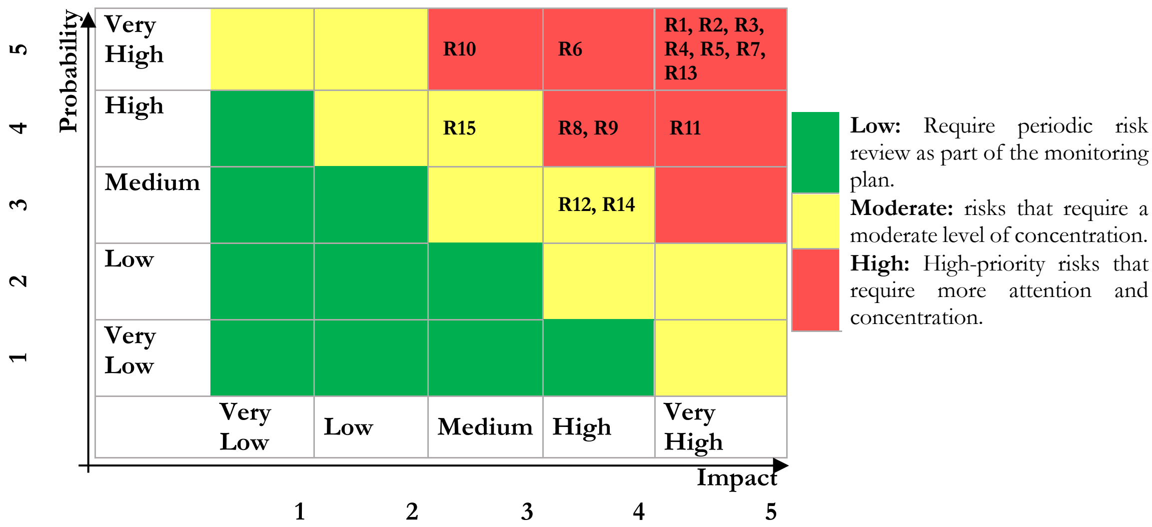


Figure 8.4 Risk Heat Map associated with the project under analysis. Source: Author' own adapted from (CGMA, 2021; McKay, 2016; Rodríguez et al., 2013)

Overall, all the risks can be labelled as High or Moderate Risks. R1 to R5, R7, and R13 represent the critical risks that require a priority analysis and review since they have the highest probability of occurrence and if they occur, they will have a high negative impact on the project. R12 and R15 represent moderate risks, or they have a medium level of risk. They are of moderate importance, this is: 1) if they occur the company can cope with them through mitigation plans. However, it is preferable to reduce the likelihood that they will occur.

The following section evaluates more accurately the type of risk identified as having the greatest potential for significant impact, namely the Business and Investment Risk.

8.3.1. Examining the Business risks: Costs and Revenues comparison

When assessing business risk, there are two main factors to analyse: the variability in sales and the operating costs. In doing so, first, this study estimated the returns (i.e. the revenues minus the costs). Revenues refer to electricity sales to local customers and depend on two factors: 1) The user's ability to pay, which is related to people's income levels, and 2) The national electricity subsidy provided by the MME. In the former case, this study assumes that people's ability to pay ranges between US $4.1 and US $5.4 per month in the off-grid areas, based on different studies implemented by the MME, the National Planning Department (DNP in Spanish) (DNP, 2016), and the most recent survey implemented by the IPSE in 2019 (IPSE, 2020a). Then, this study evaluated the cost structure of the operations, that is, how much of the operating cost is fixed cost (such as management and support function salaries; marketing (e.g., advertising, social media, promotional materials); IT service providers, IT infrastructure, equipment, consultant fees; facilities (e.g. rent, water, internet, electricity, communication costs); travel (management/ senior staff travel); other (all other costs not included above: legal fees, insurance, governance costs, extraordinary expenses, etc.) and how much is variable cost (such as commissions, transport costs, equipment, spare parts replacement, after-sales/ call centre, and mobile money/ bank charges).

Based on this information, it was estimated the number of new connections that the company should make to meet its costs, that is, to break even. Figure 8.5 shows a comparison of the minimum number of stand-alone PV systems that the off-grid utility needs to install, under three scenarios, each one with different electricity tariffs. S1 corresponds to scenario no.1 and considers the current electricity tariff approved under the CREG Res. 166 of 2020 (i.e. a monthly electricity tariff (MET) of US $31.77); S2 refers to scenario no.2 and it assumes an increase of 70% over the approved tariff (i.e. MET= US $54), and S3 refers to scenario no.3 and it uses a MET of US $ 73.41 (i.e. it corresponds to the new tariff proposed by the CREG through Res. 137 of 2020 and currently pending approval).

Regarding the subsidies scheme, in October 2020, the MME defined the subsidy applicable to the electricity tariff in off-grid areas, namely to users having stand-alone PV systems (>500Wp) for the provision of the electricity service. If the government finances 100% of the project CAPEX, the MET is about US $31.77 (i.e. assuming a monthly electricity consumption of 62.1 kWh with a stand-alone PV system of 740 Wp). From this price, the customer pays about 14% of this value, or US $4.45 and the MME covers the remaining 86%, or US $27.32 through the subsidies provided by the government. For costs and revenues associated with the project under analysis, please refer to Appendix C (Table C1).

Results from S1 suggest that the current electricity tariff *(MET=US $31.77)* is not able to cover the operational costs required for this project. When considering S2 and S3, a certain scale is required to cover the total costs. As Figure 8.5 shows, only when the MET is about US $54 (S2), potential investors can meet their costs through the annual revenues. In this case, the company would need to install at least 370 stand-alone PV systems to meet its costs. Besides, if it is considered the MET of US $ 73.41 (S3), revenues would be greater, and the company would need to install about 220 stand-alone PV systems to meet its costs.

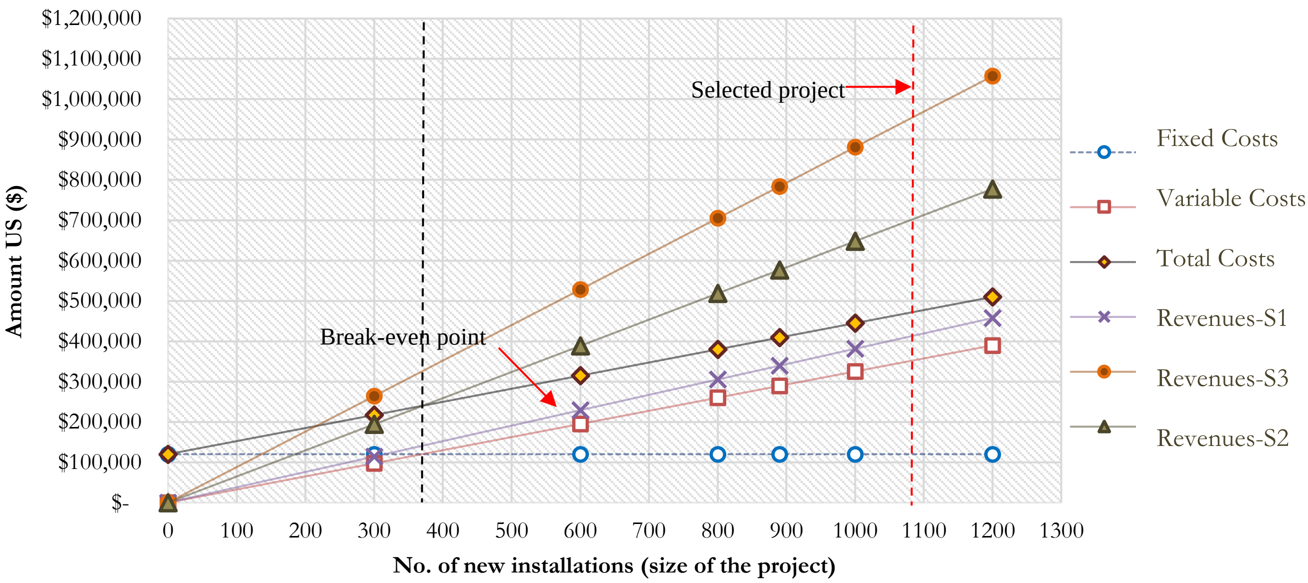


Figure 8.5 Break-even analysis for the project under analysis with three different electricity tariff scenarios

This result illustrates that profitability does not necessarily seem to be in large-scale projects (>20.000 households). When considering a MET of US $54, the private investor could reach operating break-even by providing the electricity service to a minimum of 370 households (See Figure 8.5). As highlighted by one of the interviewees, a bigger project size is not necessarily better. In business-to-customer (B2C) models, the cost of acquiring customers (CAC) in less dense populations might be larger than the lifetime value (LTV) of that customer. Therefore, it is important to focus on critical mass, particularly on regions and customers that can provide a significant average revenue per user (ARPU) for a reasonable cost of servicing that customer.

8.3.2. Investment risk analysis: NPV estimation

To assess the investment risk, this study uses the NPV adapted to conditions of uncertainty. Investment risk is the result of the variability in the value of the company's investment project or the variability in the initial disbursement of capital for a project (Crundwell, 2008). The source of this type of risk may arise, for example, from market conditions, technical implementation reasons, or the actions of competitors. This study analyses how the variability of different key inputs affects the outcome, namely the NPV of the potential project. It uses the Monte Carlo simulation to incorporate these uncertainties and quantify the potential associated risks. It considered six (6) basic inputs to the project financials: *Capital investment, Revenues, Total Costs (Fixed and Variable), Market size, Price, Lifetime of the project,* and *Discount rate.* Table 8.2 presents a summary of the values for each parameter.

Table 8.2 suggests that the capital investment in the project has not been included as this comes as a subsidy from the public funds of the government (e.g., FAZNI). Within this scenario, the government pays in advance for the CAPEX of the solution. In consequence, the investor does not provide any initial investment and thus, the company is not required to look for external funding or to claim a reimbursement of the investment once the project is in place.

Table 8.2. Input variables of the project financials

Variable	Value	Source
Capital investment	US $0 from Year 1 to Year 4 and from Year 5 to Year 10, since the MME provides 100% of the CAPEX (initial investment for the assets of the system and their installation) US$ 800/per household in Year 5 when the company assumes the battery replacement	Defined by the CREG resolution No. 137-2020
Price	$0.51-$1.18/kWh	Defined by the CREG resolution No. 166 and No.137-2020 Total kWh/month: 62.16 (Assumptions: solar PV stand-alone system of 740 Wp, 3.5 kWh/m², η=0.8, and 30 days per month)
Revenues	$31.77-73.41/month	Based on the monthly electricity consumption per customer and the potential price of each kWh (CREG resolution No. 166-2020)
Costs	Fixed: $10.000/month Variable (US $/customer): $27.1/month	Based on interviews with two off-grid utilities and project developers in rural areas of Colombia. Also, on the maximum O&M cost recognised by the CREG resolution No. 166-2020.
Discount Rate	9.7%	Defined by the CREG resolution No. 137-2020
Project lifetime	10 years	Defined by the CREG resolution No. 137-2020

The total cost structure of the project was also obtained from the semi-structured interviews. Fixed costs are about US $120,000 per year and they are set over a 10-years contract and do not vary with the size of the project, which is limited to 1262 systems (See Table A1). Similarly, variable costs are estimated from the market costs provided by the interviewed companies and the value recognised by the CREG in resolution No. 166 of 2020 (See (CREG, 2020a)). They correspond, on average, to about $27.1 per customer per month and they include the management and O&M costs (i.e. spare parts, logistic operations, preventive maintenance, and payment collection visits, among others) associated with projects located in the off-grid areas of Colombia.

Regarding the tariff scheme, the analysis simulates different tariff levels, considering the current electricity tariff approved under the CREG Res. 166 of 2020 (i.e. a monthly electricity tariff (MET) of US $31.77). This value is defined by the CREG, considering the case when the capital costs are fully subsidised by the government. Although the most recent regulation proposes a MET of US $31.77, only when the MET is about US $ 54, the company can meet its costs. Thus, this analysis assumes this value to compute the cash flows of the project and the present values at the discount rate. As a result, the NPV for the project under study is about $ 1.076.535 (See Appendix C (Table C2)), which means that implementing the project creates value for the company (i.e. with a NPV>0). This result confirms that stand-alone PV systems represent a cost-effective solution for decentralised electrification projects or a business opportunity, based on the NPV.

8.3.3. Monte Carlo Simulation with multiple sources of uncertainty

In Section 6.3.2., when estimating the NPV, it was implicitly assumed that all the elements of the cash flows were known with certainty, but, in reality, they are nonetheless uncertain. As illustrated in Table 8.1, the revenues and operating costs are the main factors whose variability can influence the long-term profit of a project. The variability in revenues or costs causes the earnings of a company to be variable, resulting in business risk. Thus, in this case, these uncertain inputs were modelled as independent random variables with probabilistic distributions, as presented in Table 8.3.

Table 8.3. Probabilistic model inputs

Input variable	Distribution	Parameters
Discount rate	Uniform	Min. 9.7% Max. 11.7%
Annual Revenues	Normal	Mean depending on the monthly electricity tariff: 1) (if MET= US $31.77) 2) (if MET= US $54) 3) (if MET= US $73.41) Standard deviation= 20% of the mean
Electricity Tariff	None	It is not modelled as a distribution because it is a decision variable, and its value is set by the CREG. However, a sensitivity analysis simulating different tariff levels was performed
Annual revenue growth rate	Normal	Mean=2.5% Standard deviation = 5%.
Variable Costs	Normal	Mean= 50% (of revenues) Standard deviation = 2% of the mean
Fixed Costs	Triangular	Min. 110,000 Most Likely. 120,000 Max.130,000 Defined by US $ 110,000 minimum, US $ 120,000 most likely value, and US $ 130,000 maximum

The NPV was estimated using Equation 6.1, for this set of values, performing a Monte Carlo simulation of 5000 iterations. As a result, the mean NPV or expected NPV, E[NPV]) when all uncertain inputs are at their means is US $ 763,438.75 and the standard deviation is US $ 501,514.25. Figure 8.6 illustrates the probability distribution of all possible results of the NPV. It shows that the project has a good probability of being profitable as suggested by its mean NPV of $145,532.58 and the NPV probability distribution. However, there is some risk involved. Approximately 93.6% of the iterations in the simulation returned a positive NPV, but 4.9% of the iterations returned a negative NPV. Also, considering the most extreme case, this project could lose over US $662,491 (minimum value).

Additionally, it was estimated the coefficient of variance for the project. It is mathematically defined as the ratio between the standard deviation of the NPV and the expected value of the NPV (Crundwell, 2008). In this case, it has a value of 0.67. This result indicates that the project risk is significant compared with its mean value, namely the variation of the results about the mean is sufficiently large that in adverse conditions the NPV may even be negative. Thus, this project can be regarded as risky. However, as highlighted in Figure 8.6, there is a 93.6% probability of getting a NPV between 0 and $2 M.

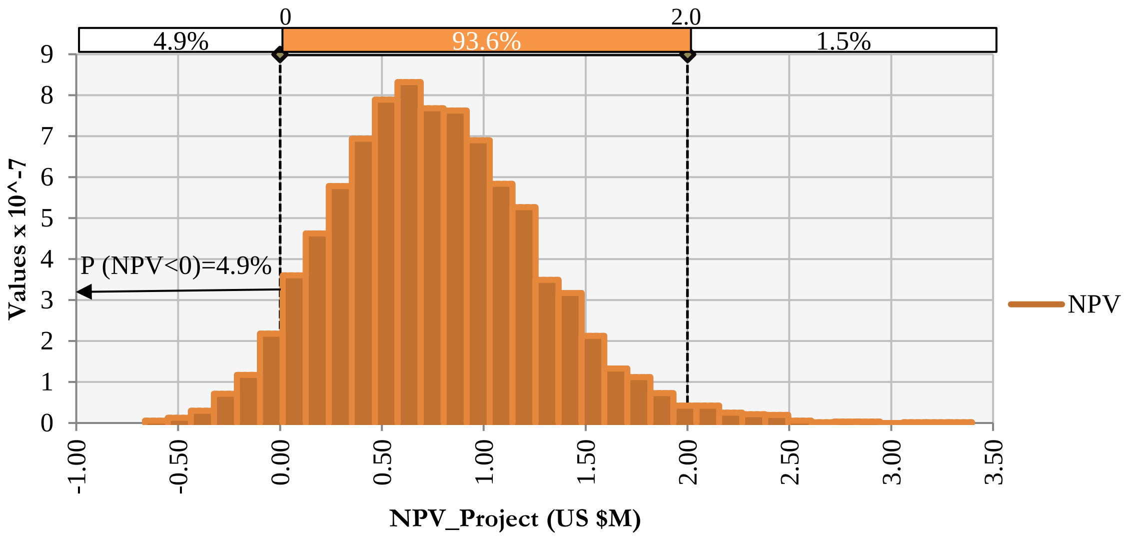


Figure 8.6 Probability density function of the NPV under scenario S2 and illustrating the value at risk.

In other words, the risk of project failure, namely that it has a negative NPV, is low. To quantify this value and assess the chances of the project failing, namely the probability that the NPV is less than zero (i.e. $P(NPV < 0)$), the value at risk or VaR of the project was estimated. In this case, this probability is less than zero, namely 0.049 or 4.9%, as presented in Figure 8.6. Although this value could represent a cause for concern to those more risk-averse investors, private investors could mitigate the potential risks through their business model.

8.4. Sensitivity Analysis

Simulating different tariff scenarios. In order to provide additional support information for the potential investor, this study runs a series of simulations, for three different scenarios: S1) With a monthly electricity tariff (MET) of US$ 37.11; S2) With a MET of US$ 54 and S3) With a MET of US$ 73.41. As a result, it was obtained different expected values for the NPV and risk profiles for each tariff, as illustrated in Figure 8.7. In this case, the three scenarios show that higher tariffs dominate lower tariff levels.

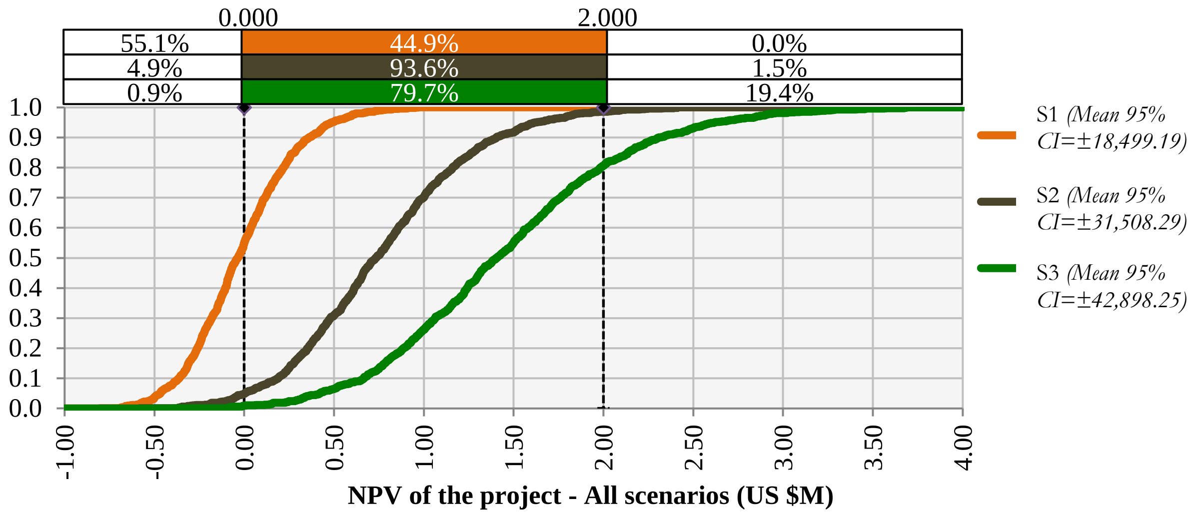


Figure 8.7 Risk profiles (overlay of cumulative ascending distributions) for the NPV under three scenarios: S1, S2, and S3 with the associated confidence interval.

Tornado graph. Finally, it was also performed a sensitivity analysis to pinpoint the most important drivers of risk of the project, highlighting those with little or no influence on the variability of the NPV (i.e. the output of the model). Figure 8.8 shows the input variables ranked in decreasing order according to the total range of the expected NPV. Each bar represents the range of the NPV values produced when each independent variable is increased (Input High) or decreased by 10% (Input Low), with the other variables being held constant.

In this case, the variability in *Annual Revenues* and the *Annual revenue growth rate* are the most impactful variables to the variability of the project's NPV, in a non-linear manner as illustrated in Figure 8.8. However, even with a 10% reduction in both variables, the project is still economically attractive (i.e. NPV>0). In particular, the *Annual revenues* produce the largest range of the NPV (from US $ 88,933.9 to $ US $1,386,630.11) and thus, it is at the top of the chart.

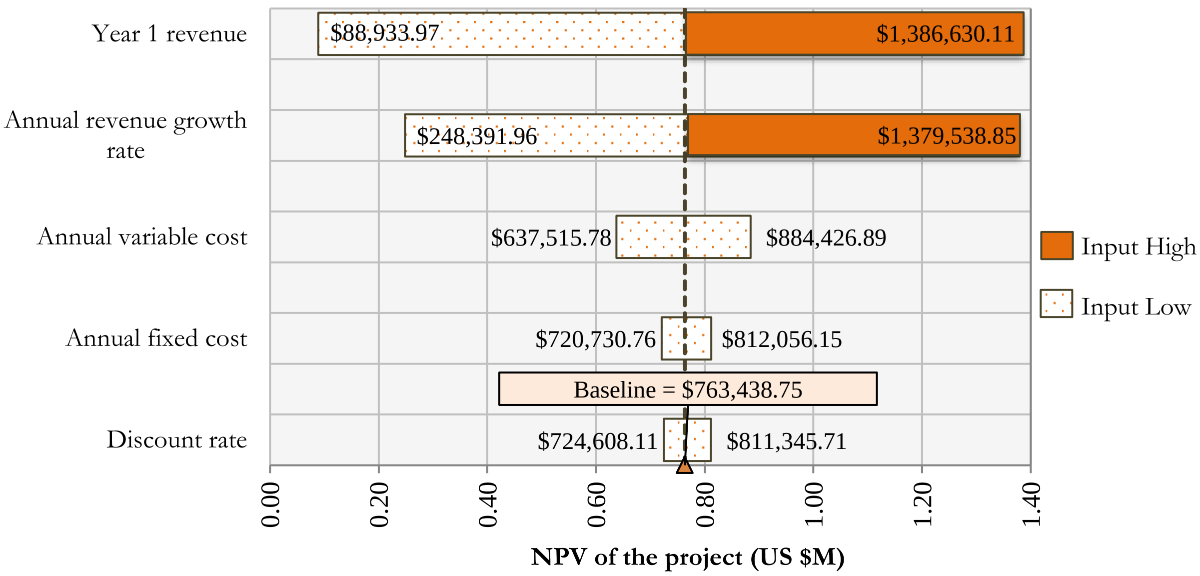


Figure 8.8 Tornado plot of the effect of the independent variables on the NPV.

8.5. Chapter Summary

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Risk assessment is a key aspect to consider when implementing rural electrification projects. This process allows to identify, analyse, and evaluate potential risks that could impact the success of the project. This chapter presented a set of uncertainties and derived risks affecting the private sector participation in the rural electrification sector and implemented a stochastic discount cash flow technique — net present value (NPV) combined with Monte Carlo simulation — to incorporate these uncertainties and quantify the business and investment risks associated with an off-grid solar PV project. Using the case of Colombia, it was possible to identify the most critical variables influencing the NPV of the project by implementing a sensitivity analysis. As a result, major contributors to risk are the variability in revenues and the annual revenue growth rate. For this case, this study estimates the probability of project failure and investigates how private companies could mitigate risks by keeping operating costs to less than 50% of revenues. In this regard, the role of the government proves to be essential in providing a better investment environment for private investors. Additionally, these results highlight the importance of considering the poverty analysis together with the site prioritisation assessment (See Chapter 6 and Chapter 7) within the risk assessment process. Selecting the target market for investment and accounting for its socioeconomic characteristics are some of the most important factors impacting the company's revenue growth. Based on an in-depth knowledge of the community, better marketing and sales campaigns that adapt to people's income can be designed to incentivise customers to regularly pay for the service. Thus, social interventions from the beginning of the project prove to be essential and this requires support from different local authorities of government. Additional potential derisking measures are suggested in Chapter 10.

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9. Providing electricity access in remote and rural areas: the role of decentralised solutions and energy efficiency measures

One of the possible solutions to providing electricity access in remote rural areas is considering the application of minigrids (MG) technologies. MG provide several technical advantages, including reduced transmission losses, limited upfront capital expenditure, and the ability to accommodate on-site, renewable generation. Using the case of Colombia, this chapter presents a techno-economic evaluation of different off-grid technologies vs the current diesel-powered plants, based on the LCOE. The objective is to contribute to an integrated energy planning for the development of microgrids, making them a more feasible energy solution for off-grid areas. Results indicate that hybrid minigrids represent a potential alternative to decarbonise the off-grid sector and improve electricity access. In addition, this chapter examines the role of energy efficiency measures in expanding electricity access in rural areas, based on qualitative and quantitative research methods. Results confirm the need to implement energy efficiency measures for specific appliances to maintain levels of energy demand, which could impact companies' revenues, and thus, electrification investments could grow within the unelectrified off-grid areas. Overall, these results are of interest not only to off-grid energy providers seeking to guarantee revenues but also to policymakers working on defining public interventions in rural areas as a booster of achieving higher levels of electricity access in developing countries.

This chapter uses the case of Colombia with two main purposes: 1) to evaluate the technical and economic feasibility of hybrid minigrids and 2) to understand consumer demand and preferences for off-grid appliances and to develop estimates of electricity-consuming appliance ownership as a proxy for an economically sustainable level of residential electricity in surrounding areas that do not currently have access to electricity.

9.1. The role of decentralised systems in the rural electrification sector of Colombia

Historically, the energy provision in the ZNI has depended on fossil fuels. Currently, nearly 98% of the off-grid localities in the ZNI are attended by diesel-powered plants. In particular, 88% or 255.677 kW of the installed capacity in these areas comes from diesel-powered plants, requiring about 2.8 million gallons per month (gl/month) to serve a total of 158.251 families (as of December 2021) (IPSE, 2021b). San Andrés and Providencia, Choco, and Nariño, correspond to the three departments with the highest installed capacity for diesel (See Figure 9.1).

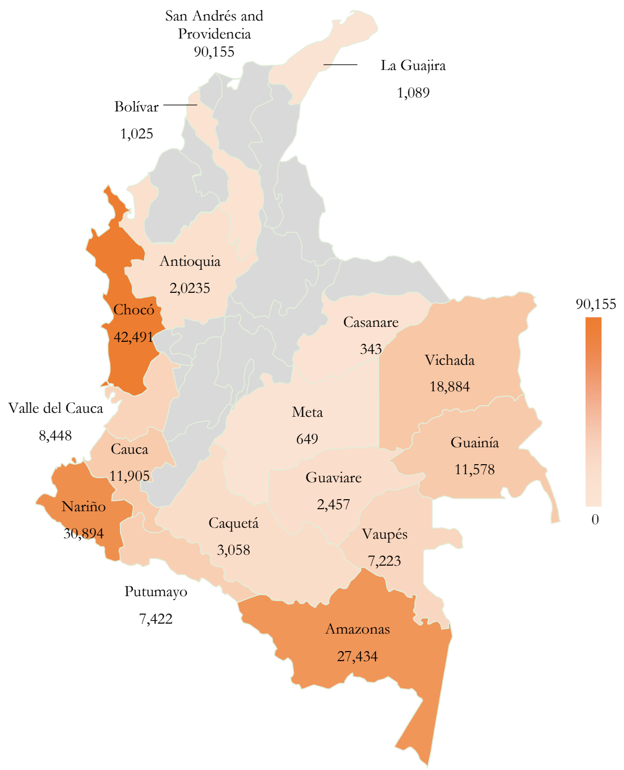

Figure 9.1 Installed capacity with diesel generation (kW). Source: Authors' own adapted from: (IPSE, 2021b).

Table 9.1 Distribution of localities by type of Micro-grids installed in the off-grid areas of Colombia (as of July 2021)

Technology	No. of localities
Diesel and Municipal solid waste (MSW) plants	1
Solar PV	1
Solar PV and Diesel	19
Biomass and Diesel	2
Small hydropower	4
Small hydropower and Diesel	15
Diesel	1735
Total	1777

The majority of these diesel minigrids correspond to unreliable systems that are unable to provide power for social infrastructure and services including health, education, and public lighting. Where diesel minigrids are available, municipalities and operators are affected by unreliable and costly maintenance of external diesel provision, which has negative knock-on effects on economic development. In addition, due to the ZNI characteristics, the costs of providing electricity services tend to be high because most ZNI rely on diesel as fuel for generation, which generates high operating and transportation costs, as well as negative effects on the environment and the ecosystem surrounding the community, especially for the transportation of fuel to the specific locality. Not only the transport of diesel is particularly complex due to the geographic specificities (e.g. mountainous ranges and rivers), but also there are illegal activities in these rural areas that lead to theft and therefore leave these communities without energy for long periods. In addition, from this set of localities, only 110 of them, or less than 10% have a metering system locally installed to monitor the electricity provision quality (CNM, 2022).

Overall, the provision of electricity service with diesel-powered minigrids is mainly hindered by the following aspects:

- These energy systems provide intermittent and poor-quality service to off-grid communities. In particular, the energy service provided in the ZNI varies among villages. While 37% of users have access to electricity 24 hours a day, nearly 43% of users (in 86% of localities) receive electricity service for a few hours a day (between 4 and 5 hours) (CNM-IPSE, 2021). This condition negatively impacts the well-being of the population in the ZNI, in social, productive, and economic terms.
- The use of increasing diesel is associated with current minigrids in the ZNI. In nearly 20% of the localities, diesel generators operate with an efficiency lower than the efficiency regulated by the CREG resolution 091 of 2007, which ranges between 25% and 35%. Therefore, in localities where diesel generators operate under lower efficiencies than that, it is likely that the fuel will not be able to provide the service during the defined time, or what is equivalent, they need more fuel to generate 1 kWh of energy compared to localities with more efficient machines.
- Using diesel as fuel for generation generates high operating and transportation costs, especially for the transportation of fuel from the distribution point to the specific locality. According to the SSPD's information system (SUI in Spanish), where energy service providers of the ZNI report their commercial information, the electricity cost ($/kWh) in nearly 80% of the localities is between $0.27/kWh and $0.54/kWh (SSPD, 2022) (See Figure 9.2). This cost depends on three components: generation, distribution, and marketing costs, according to the CREG resolution No. 091 of 2007 (CREG, 2007). In the case of the ZNI, the Generation component (including recognised losses) weighs 84% of the total electricity cost; the Distribution component, 6.4%, and the Marketing cost 8.7% (SSPD, 2021a).

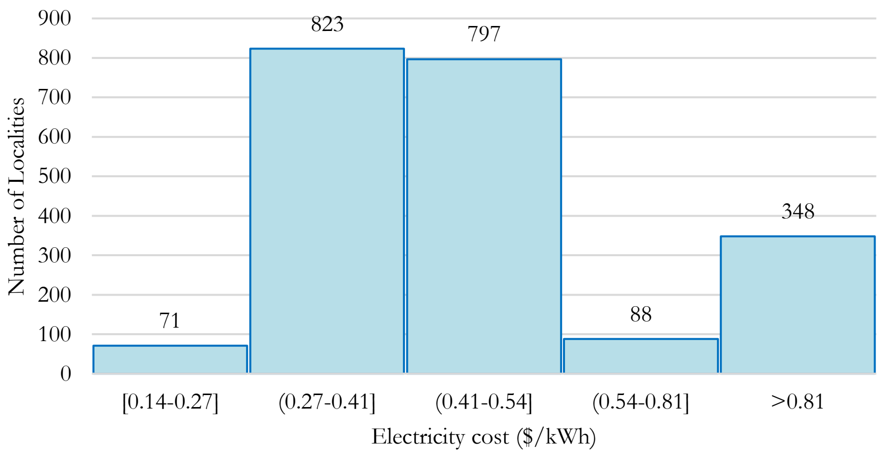

Figure 9.2 Average electricity cost ($/kWh) in the ZNI-2021. Source: Author's own from (SSPD, 2022)

Unfortunately, the cost of providing electricity service in the ZNI is almost three times higher than the electricity cost in the SIN, which corresponds to about $0.18/kWh. As a result, to protect users of the ZNI from high electricity costs, the government covers this difference by providing a monthly subsidy, based on the MME resolution no. 182138 of 2007.

- The use of diesel has negative effects on the environment and the ecosystem surrounding the community. According to the current MME resolution that will define subsidies for users in the ZNI (MME, 2022a), the CO_2 emission factor of the ZNI (855 gr/kWh)is nearly 4 times higher than the emission factor of SIN (203 gr/kWh).
- According to the 2018 SSPD report, the cost of the subsidy per user of the SIN is US $35.53 per year, while the cost per user of the ZNI is US $375.36. This comparison shows that the

subsidy allocation for users of the ZNI has a higher fiscal impact on the government budget relative to users of the SIN. In particular, the annual cost of the subsidy per user of the ZNI is 10.5 times higher than in NIS.

Thus, off-grid RE-based systems are a promising alternative not only to diversifying the energy matrix of the ZNI, but also to reducing greenhouse gas (GHG) emissions from the use of fossil fuels, lowering the electricity service costs, increasing energy efficiency, and improving the quality of the electricity provision in these areas (IPSE, 2022).

During the last decade, the GoC has set different policies to achieve this purpose. In 2014, the MME set a national policy (Art. 9 of Law 1715-2014) aimed at implementing a program that progressively substitutes diesel generation in the ZNI with more efficient energy systems. In addition, in 2015, during the United Nations Framework Convention on Climate Change (COP 21), the Colombian government ratified its commitment to the fight against climate change and set the compromise to reduce national GHG by 20% by 2030. Then, in 2020, under the energy transition of the current government, this commitment was modified to reduce 51% of the national GHG by 2031 (Ministerio de Ambiente, 2020).

The most recent indicative national plan for expanding electricity access (PIEC 2019-2023 in Spanish) indicates that on average more than 70% of the households of the five departments with the highest number of households without electricity access (as of 2018), namely La Guajira (81,960), Narino (36,264), Cauca (32,275), Choco (29,558), and Valle del Cauca (27,782) will gain electricity access through off-grid decentralised systems (UPME, 2019a), as presented in Figure 9.3.

Although the cost of deploying hybrid RE-based minigrids has been continuously reducing rapidly, in the off-grid areas of Colombia, the LCOE for this type of technology range between US $0.4/kWh and $0.60/kWh (CREG, 2019; Haghighat Mamaghani et al., 2016), which is still a challenge to attract private investors compared to the electricity cost in the SIN (~US$0.18/kWh). The particular geographical conditions of remote off-grid areas, coupled with a low-density population represent some of the key barriers to consider when determining whether the electricity supply provision should be grid expansion or off-grid, based on the LCOE.

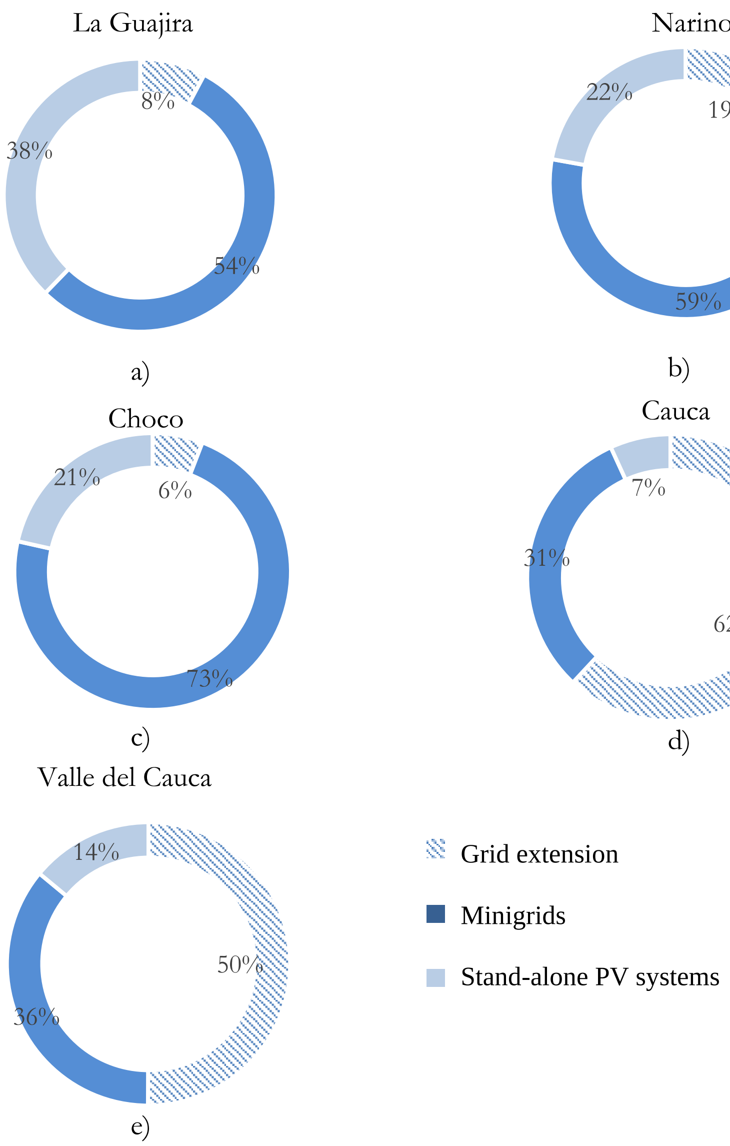

Figure 9.3 Distribution of off-grid energy solution to achieve universal access in five departments of Colombia. Source: Adapted from (UPME, 2019a)

9.1.1. Case study

The first part of this chapter evaluates the potential of hybrid energy systems (i.e. solar PV/diesel system with BESS) in one off-grid area of Colombia where there is a high dependency on diesel-powered plants. For this purpose, a case study of a typical off-grid village whose electricity provision depends on diesel-powered generation is analysed.

Choco, Nariño, and Cauca correspond to the three Colombian departments with the highest number of installed diesel-powered plants: 554, 536, and 159, respectively. In this case, the analysis was focused on the community of San Juan de La Costa, Nariño, where the electricity provision depends exclusively on a diesel-based minigrid.

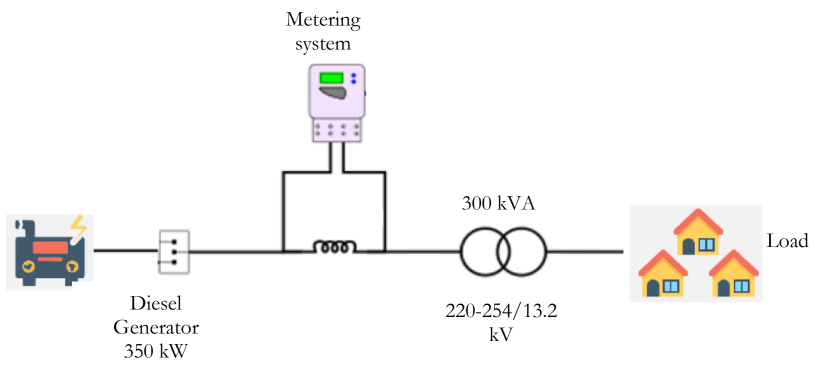

Figure 9.4 Schematic of the current energy system installed in the community of San Juan de la Costa, Narino (Colombia).

The current energy system has an installed capacity of 350 kW to attend to 400 users. However, the power peak demand is 121.6 kW or 304 W per household, and the whole community has a monthly energy consumption of about 22,030 kWh distributed for nearly 8 hours and 33 min per day. Figure 9.5 shows the typical daily electricity consumption profile for a household in this village. It has two demand peaks, one during the noon from 10:00 to 14:00 and the second during the evening from 15:00 to 21:00. The second peak gives an idea of the maximum load that is required from the diesel-powered minigrid (i.e 121.6 kW in February of 2022). However, the current installed capacity is almost three times higher than the peak demand of the community, which evidences that the generation system is oversized. Unfortunately, this scenario replicates about 20% of the localities with monitoring systems in the off-grid areas of Colombia.

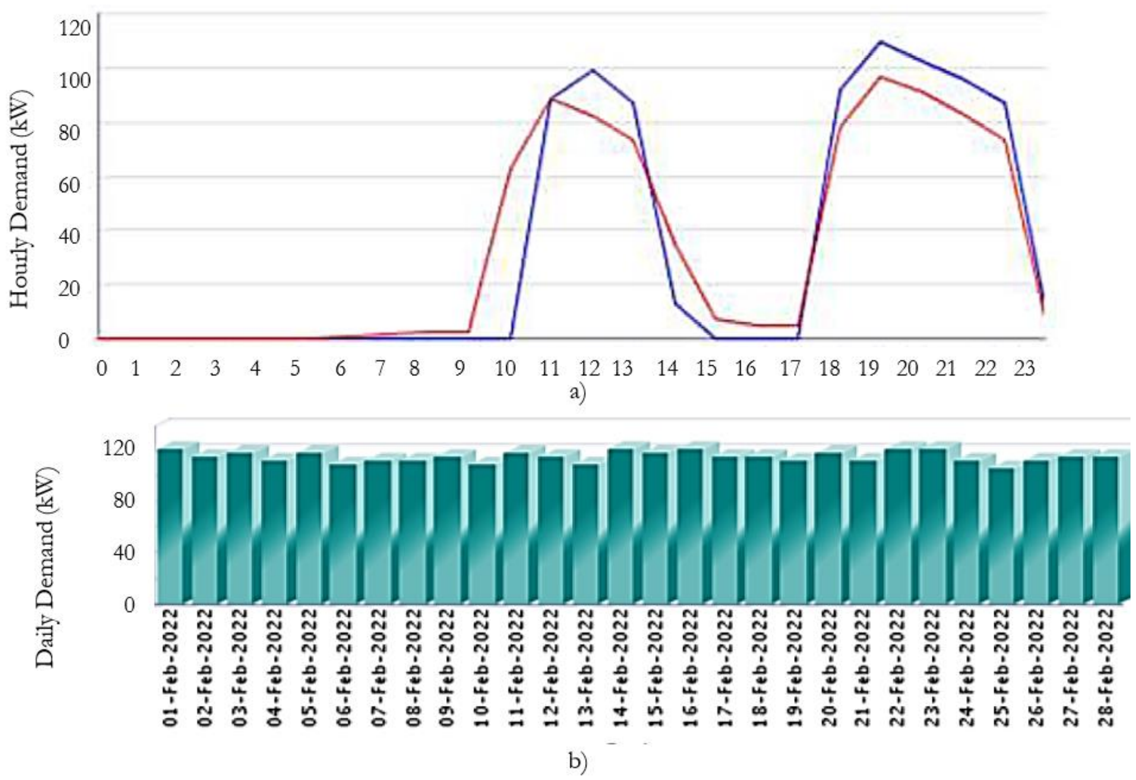

Figure 9.5 a) Daily household electricity demand profile and b) Daily peak demand associated with the community of San Juan de La Costa in February 2022. Source: (CNM, 2022)

9.1.2. System modelling: local resources, load demand, and costs

In this case, HOMER simulates three different minigrid configurations or scenarios (See Table 9.2) to compare the performance of the hybrid energy system with different energy systems. For each comparison, the total net present value, the LCOE, and the CO_2 emissions are estimated.

Table 9.2 Simulated scenarios in HOMER. Source: Adapted from (Oviroh and Jen, 2018)

Scenario 1	The energy provision depends 100% on the diesel generator, which is used to make the comparison with scenarios 2 and 3
Scenario 2	Solar PV panels provide the required energy to the community and store the excess energy in the battery to be used at night or when there is insufficient radiation to provide the required energy.
Scenario 3	The solar PV panels provide the required energy to the community during the day time and the diesel generator is forced to start between 10:00 p.m. and 7:00 a.m. In between the times when there is no sufficient solar radiation to provide the required energy, the battery supplies the required energy.

Figure 9.6 shows the schematic diagram of the proposed scenarios. The solar PV-diesel system comprises a solar PV array containing the solar modules, converter, batteries for storage, the diesel generator, and the load.

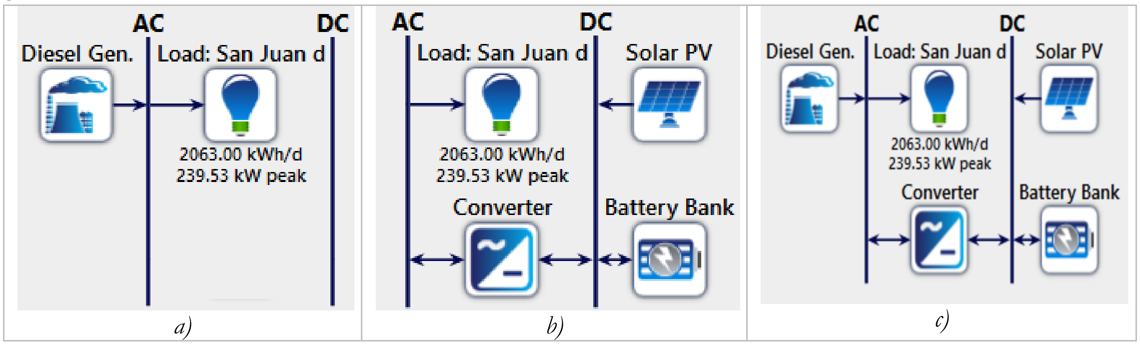

Figure 9.6 Schematic diagram of the simulated scenarios in HOMER. Source: Retrieved from HOMER Pro 3.14.1

Solar energy resource. According to Colombia's solar radiation atlas, the country has good solar energy potential throughout the territory, with a daily average of 4.5 kWh/m2 (IDEAM, 2015a), suitable for the appropriate use of this energy resource, with the enormous advantage that the solar radiation is nearly uniform throughout the year. San Juan de la Costa has a solar radiation of 4.66 kWh/m²/day. Figure 9.7 shows the daily average of global solar radiation and the clearness index for these selected communities.

Figure 9.7 Daily average of global solar radiation and the clearness index in San Juan de la Costa. Source: Retrieved from HOMER Pro 3.14.1

Wind energy resource. On the Colombian territory, a weak wind flow predominates with speeds of up to 3 m/s in rural areas located between the departments of the Pacific region, including the department of Nariño and thus the locality of San Juan de la Costa. shows the wind speed in the department of Nariño at 10m height.

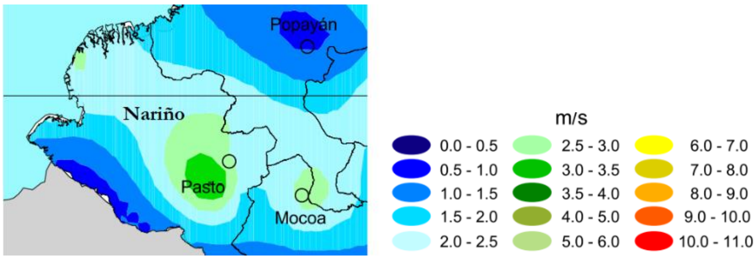

Figure 9.8 Annual average wind speed for the department of Nariño. Source: (IDEAM, 2015b)

The average wind speed for San Juan de la Costa is always below 4 m/s. These wind speeds are considered very low considering that energy generation is being considered for isolated generation systems. Using these wind speeds involves the implementation of low-speed wind turbines either vertical or horizontal whose powers are low and highly variable and do not provide a reliable and constant power solution for communities.

Load Demand. Since the electricity service in the locality under analysis is provided for less than 10 hours per day, a new projected load demand profile was included in HOMER, considering the 24 hours of service that would be provided by the potential low-carbon minigrids. Based on the typical demand profile for the ZNI, proposed by the CREG (CREG, 2005), the daily demand profile for the community in San Juan de la Costa was adjusted, as presented in Figure 9.9.

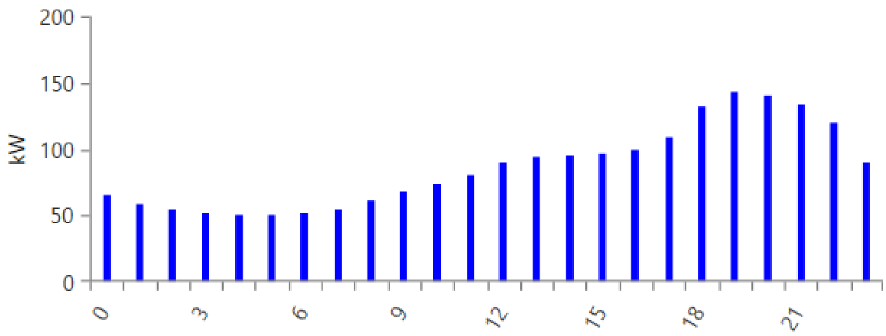

Figure 9.9 Daily demand profile in San Juan de la Costa. Source: Retrieved from HOMER Pro 3.14.1

Diesel fuel price. The current diesel price in the department of Nariño is about US $0.43/L (as of 2021) (SSPD, 2021b). However, in rural areas and during fuel scarcity, the diesel price may be significantly higher than the official price.

9.2. Results and discussion

In order to analyse the interest in the hybrid system in comparison with the conventional stand-alone installation (Diesel generator). Table 9.3 presents the comparison of the aforementioned three scenarios in terms of the LCOE. Results suggest that Scenario 3 results in the best design with the lowest LCOE. Thus, the cost of generating electricity using a hybrid solar PV and diesel energy system is cheaper than using only a conventional diesel-based system.

Table 9.3 Results for the different scenarios in San Juan de la Costa

	Scenario 1 (Diesel)	Scenario 2 (Solar PV)	Scenario 3 (Solar PV and Diesel)
LCOE (US$/kWh)	0,42	0,86	0,37

Figure 9.10 shows the electricity supply breakdown for scenario 3, where the orange bars represent the power produced by solar panels, while the green ones show the power generated by the diesel generator. Also, Table 9.4 shows the optimal system design of the low-carbon minigrid that can meet the specified load, compared to the current diesel-powered minigrid. The hybrid system (scenario 3) is the optimal option, using a renewable fraction of 50.4% while covering the load demand required.

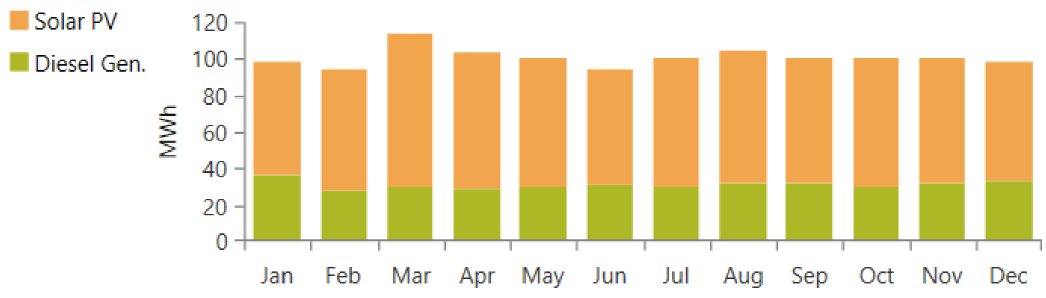

Figure 9.10 Monthly electricity production in Scenario 3.

Table 9.4 Comparison between the optimal scenario and the conventional diesel-powered minigrid

Technical Specifications	**Scenario 3 (Solar PV and battery backup + Diesel)**	**Scenario 1 (Diesel)**
PV (kW)	600	0
Diesel Generator (kW)	150	350
Converter (kW)	35,4	0
Battery Bank (kWh)	973	0
Battery Autonomy (hr)	5.31	0
PV (kWh/year)	836,213	0
Diesel (kWh/year)	373,119	742,704
Total Fuel (L/year)	89,988	446,082
Renewable fraction (%)	50.4	0
CO_2 emissions (kg/year)	319,017	635,012

The amount of fuel consumption (in L/year) of the hybrid energy system decreases by 80% compared to the conventional system. The hybrid configuration results in an emission of 319,017 kg CO_2/year, which is about 50% less than the resulting emission of the diesel-based system (635,012 kg CO_2/year). This is equivalent to over US $153,45276/year which can be economised during the lifetime of the project (15 years).

In addition, Scenario 3 guarantees a reliable electricity supply for 24 hours per day, compared to the nearly 8 hours provided by the current system in the locality under analysis. Therefore, implementing this type of low-carbon system in off-grid communities has the potential to increase their level of economic productivity and thus, their standard of living.

However, there are still key challenges to guaranteeing the long-term sustainability of minigrids and they mainly relate to: (i) lack of a regulatory framework that sets effective tariffs and business models that guarantee financial closure for private investors; (ii) lack of capacity building or training provided to the community on how to use the energy service; (iii) lack of community interaction and engagement during the system planning stage; (iv) the lack of long-term contracts that guarantee the O&M of the systems; (v) the lack of synergies between access to electricity and other sectors, such as telecommunications, water, agriculture, among others, which affects the community engagement in sustaining the systems; and (vi) poor project supervision provided (Akinyele et al., 2018).

9.3. High-performing appliances as a potent catalyst for scaling energy access in off-grid areas

Between 2013 and 2020, Colombia's energy and mines planning division (UPME in Spanish) led the formulation and implementation of 10 Sustainable Rural Energisation Plans (PERS in Spanish) in the departments of Nariño, Tolima, La Guajira, Choco, Cundinamarca, Orinquia, Putumayo, Norte de Santander, Cesar, and Guaviare. These plans have provided a diagnosis of the socio-economic characteristics and estimates about the electricity demand and the level of appliance ownership of about 20,000 local rural households in the country. In addition, between 2020 and 2021, the Institute for the planning of Energy Solutions in the off-grid areas of Colombia (IPSE in Spanish) released the results of a nationwide survey that gathered socioeconomic, and energy needs information from more than 12,000 rural households located in the off-grid areas of Colombia.

This chapter particularly uses the case study of La Guajira, the region with the highest deficit in electricity access in Colombia (UPME, 2019b). The goal is threefold: First, it particularly focuses on identifying the appliances driving the household's electricity consumption, namely those appliances that could drive the demand for off-grid energy such as solar home systems (SHSs) and minigrids. Second, it implements an econometric diffusion analysis to explore the influence of socio-economic factors (i.e. income, electricity access rate, and percentage of rural population) on ownership of selected household appliances in rural areas with current electricity service. Finally, it estimates the potential electricity demand in surrounding areas that do not currently have access to electricity, considering energy efficiency improvements in selected appliances.

It particularly studies the influence of key socio-economic indicators, namely household income, the electricity access rate, and the index of rurality on Refrigerator ownership.

Based on these results, this study proposes energy efficiency interventions that could enable the widespread of off-grid energy technologies and more efficient appliances in rural areas of Colombia. This analysis is relevant not only to policymakers but also to off-grid project developers, seeking to provide energy services in off-grid areas of developing countries.

9.3.1. Case Study

La Guajira was used as a case study. This Colombian department spans over 21.000 km^2 of the national territory within 15 municipalities (See Figure 9.11). It has the highest deficit in electricity access in the country, accounting for about 80.000 households or nearly 320.000 people without access to electricity service (UPME, 2019a).

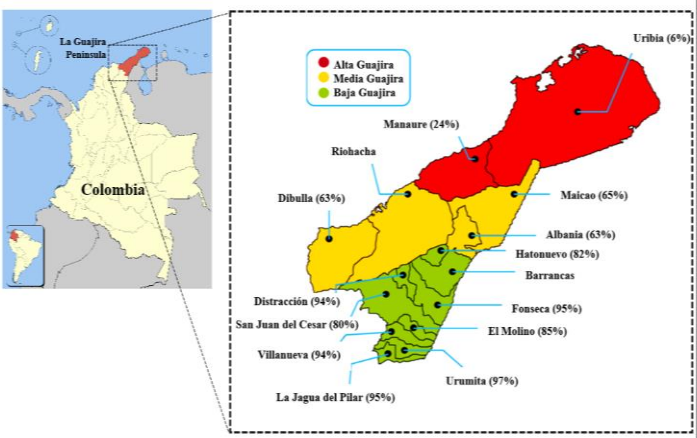

Figure 9.11 Map of La Guajira with the distribution of electricity access rates among the 15 municipalities and subregions. Source: Adapted from (UPME, 2019b, 2015)

La Guajira is divided into three large subregions according to the diversity of their socio-economic, cultural, and geographic characteristics. These are known as: "Alta Guajira" (Upper Guajira), "Media Guajira" (Middle Guajira), and "Baja Guajira" (Southern Guajira), as presented in Figure 9.11. These areas exhibit the following socio-economic characteristics: 46% of La Guajira population (or nearly 400.000 inhabitants) corresponds to indigenous people (UPME, 2015); a high index of rurality: 53% corresponds to the rural population (as of 2018); nearly 40% of the population do not have access to the electricity service; the provision of basic services for the population is very deficient and sometimes unavailable (Vides-Prado et al., 2018); lack of local infrastructure (i.e. roads, sanitation, and water services); low levels of payment capacity; high difficulties in payments collection; topographic complexity (i.e. nearly 40% of the region corresponds to arid and desertic land); and nearly 53% of people have unsatisfied basic needs (UBN). In addition, there are differences in poverty levels within regions. In particular, Alta Guajira is the area with the most severe economic conditions (DANE, 2018; IDB, 2016; UPME, 2019b, 2015).

The model implemented here captures key household appliance ownership drivers such as income, electricity access, and the rurality index, based on the approach described in McNeil and Letschert (McNeil and Letschert, 2010) and described as follows:

- *Appliance ownership:* This variable is defined as the ratio of the appliance stock to the total number of households. Data on appliance ownership were the RSEC carried out in La Guajira, in 2014, within the framework of the PERS.
- *Household income:* This variable corresponds to the average monthly household income in each municipality.
- *Electricity access rates:* It corresponds to the percentage of the population with electricity access in rural areas. Data were obtained from the most recent report about the national electricity coverage index per municipality, presented by the UPME, in 2018.
- *Index of Rurality:* This variable is a measure of rurality or the percentage of rural population at the municipality level. These values are taken from the most recent national census of 2018, conducted by the Colombian Statistical Service or DANE (its acronym in Spanish).

9.3.2. Results and Discussion

Reported appliance ownership. According to (Coalition Energy for Access, 2019), penetration of household appliances is low in rural areas of the world. In fact, in rural Africa, the penetration is even lower: 4% for refrigerators and 18% for televisions.

This section provides evidence about the reported appliance ownership in rural households of La Guajira. Figure 9.12 shows that of the 1,255 surveyed households more than 70% own a TV. The ownership of other appliances is uneven among the subregions. While more than 45% of the households in the Middle and Southern Guajira own a refrigerator and a fan, this share is below 15% for both appliances, in the Upper Guajira. In addition, blenders report higher ownership in the Middle and Southern Guajira than in the Upper Guajira.

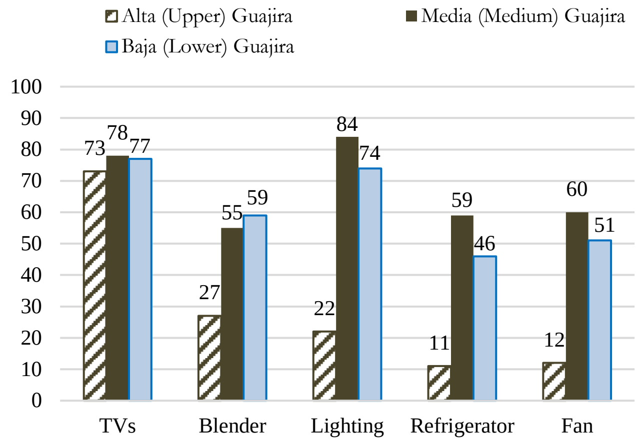

Figure 9.12 Reported appliance ownership in La Guajira."RF" stands for Refrigerator, "WM" stands for washing machine, and "TV" stands for Television.

Also, there are disparities in lighting ownership among subregions. According to the results of the survey, the main source of lighting used in the Middle and Southern Guajira subregions is electricity, while in the Upper Guajira more than 50% of the households use batteries as the main source of lighting (PERS-Guajira, 2016). Facing the lack of electricity service in this region, users have looked for other sources of lighting, including batteries and candles.

In addition, where electricity service is available, 60% of households use incandescent light bulbs while 40% use energy-efficient lighting.

Electricity demand per end-use process. Table 9.5 shows in detail the monthly electricity consumption (MEC) per household, disaggregated within each end-use and considering the set of appliances used by more than 50% of the households in each subregion.

On average, in the Middle and Southern Guajira, the MEC ranges between 171.8 kWh and 179.9 kWh, while in the Upper Guajira, levels of electricity consumption correspond to about 142.4 kWh/month. In the Upper Guajira, the energy demand is significant for lighting compared to electrical appliances. One explanation for this difference could be related to the lack of electricity supply in this sub-region (See Figure 9.11) coupled with the local economic conditions that prevent the acquisition of off-grid appliances.

Table 9.6 presents the electricity consumption share by process or end-uses for each of the subregions. In this case, results indicate that on average, refrigerators account for about 42.3% of residential electricity consumption. Lighting ranks second, accounting, on average, for about 23% of the electricity consumption followed by fans (21%) and televisions (14%).

Appliance ownership and electricity access. This section particularly focuses on describing the relationship between refrigerators and fan ownership compared to electricity access rates since they correspond to the appliances driving households' electricity consumption in La Guajira (See Table 9.6). Figure 9.13 and Figure 9.14 show the observed trend in Fans and Refrigerators ownership and electricity access. Each dot represents each of the 15 municipalities of La Guajira.

Table 9.5 Average Monthly energy consumption (MEC) of household appliances

Region	End-use equipment	Power [W]	Quantity	Average hours of usage per day	MEC [kWh]
Upper Guajira	Lighting	100	2	4	23,5
	TV	122	1	4	14,3
	Blender	350	1	0,16	1,6
	Refrigerator[a]	200	1	16	94,1
	Mobilephone-charger	50	1	6	8,8
	Total				*142,4*
Middle Guajira	Lighting	100	2	4	23,5
	TV	122	1	6	21,5
	Blender	350	1	0,16	1,6
	Refrigerator	200	1	16	94,1
	Washing machine	400	1	2	3,4
	Fan	80	1	8	18,8
	Mobilephone-charger	50	1	6	8,8
	Total				*171,8*
Southern Guajira	Lighting	100	2	4	23,5
	TV	122	1	8	28,7
	Blender	350	1	0,25	2,6
	Refrigerator	200	1	16	94,1
	Washing machine	400	1	2	3,4
	Fan	80	1	8	18,8
	Mobilephone-charger	50	1	6	8,8
	Total				*179,9*

[a]where available

Table 9.6 Electricity consumption per end-use process

End-use process	Monthly electricity consumption shares by process [%]		
	Alta Guajira (Upper)	***Media Guajira (Middle)***	***Baja Guajira (Southern)***
Lighting	28	19	22
TV+ mobile phone charging +Stereo	12	15	15
Refrigeration	34a	49	44
Fan	26	17	19

[a]Only 11% of the households own a refrigerator

These results reflect important trends in the "appliance ladder" (Fabini et al., 2014) which describes the order and manner in which electrified rural households of La Guajira, acquire electricity-consuming appliances. In this case, results show that fans are more common than refrigerators (See Figure 9.13 and Figure 9.14). This comparison reflects the moderate capital cost and energy consumption and the less stringent reliability requirements as compared to refrigerators. In addition, fan ownership levels reflect that electricity access can be viewed on a continuum. Basic low-power applications, such as lighting, are the first tier. Moving up the continuum requires that off-grid systems be capable of running higher-power appliances such as fans. Meanwhile, the level of refrigerators ownership is significantly below electricity access.

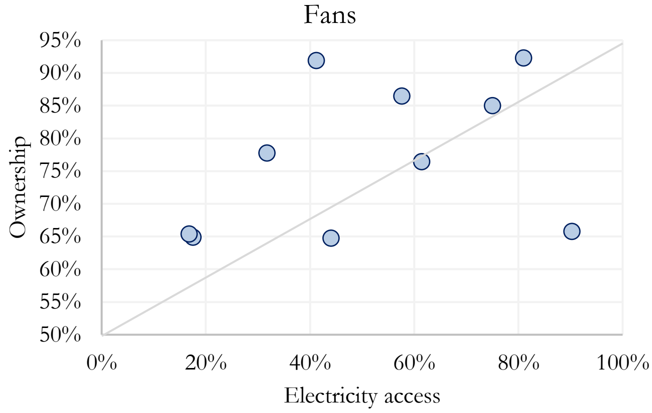

Figure 9.13 Electricity access vs Fans ownership

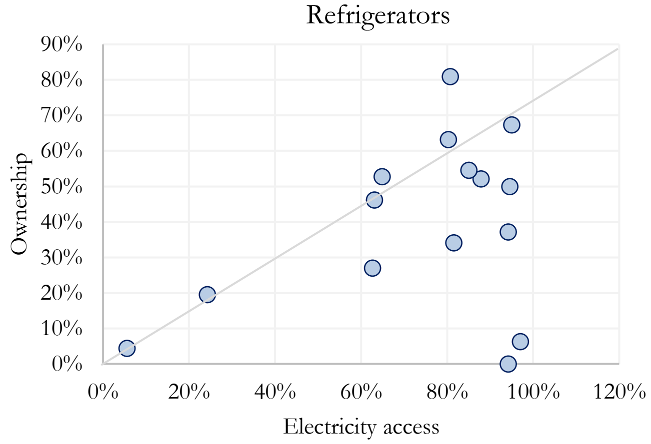

Figure 9.14 Electricity access vs Refrigerators ownership

Figure 9.14 suggests people acquire refrigerators depending on the level of energy access they have. As a result, key factors such as the high capital cost of the appliance, the relatively high electricity consumption, and the high reliability of electricity service required hamper refrigerators acquisition in rural communities.

Regression Analysis. When implementing the econometric diffusion modelling, this analysis particularly focused on studying the influence of key socio-economic indicators, namely the household income, the electricity access rate, and the index of rurality on Refrigerator ownership. This appliance was selected since it accounts for the highest share (~42.3%) of the households' electricity consumption in La Guajira. For refrigerators, α is assumed to be 1, according to the current maximum observed ownership of refrigerators within the regions.

Table 9.7 shows the results of the linear regression for refrigerators. With an R^2 of 0.91, results reveal that refrigerator ownership data is very well described by a logistic functional form with electrification rate, income, and index of rurality, as independent variables. Electricity access rate and the index of rurality are statistically significant determinants of refrigerator ownership and influence the overall performance of the model. These parameters also have the expected sign, that is, ownership increases with increasing electrification and decreasing level of percentage of the rural population. Income, however, was not found to be a significant variable for this appliance; therefore, this variable was eliminated in the linear regression.

Table 9.7 Regression model results

Parameter	Coefficient[a]
Interception	1.72 (0.73)
$\boldsymbol{EA_m}$	-3.01 (0.41)***
$\boldsymbol{RI_m}$	-1.39 (0.28)***
Observations	15
R-squared	0.91

a. Standard errors of estimates are presented in parenthesis. ***p ≤0.01

Figure 9.15 shows the linear regression results for refrigerators and electricity access rates. Results indicate that rural electrification explains diffusion rates for refrigerators. As expected, refrigerator diffusion follows a close relationship with rural electrification which suggests that most households with access to electricity will purchase a refrigerator if they can afford to buy one. When evaluating the robustness of the model, the distribution of errors between the model and the reported data for the regions was estimated. This calculation gives an error of 3% for refrigerators.

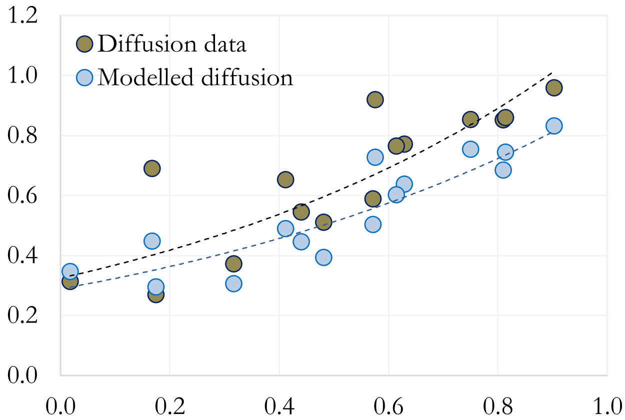

Figure 9.15 Diffusion model for refrigerators vs electricity access

Energy efficiency measures. Improving electricity access rates cannot only depend on the number of new connections but on the improvement of people's quality of life. Thus, increasing the electricity coverage may be oriented not only to enable access to a basic service but to facilitate and promote productive and social uses of the installed infrastructure.

In this matter, efficient off-grid household appliances are critical not only for increasing access to energy-dependent services but for reducing the electricity consumption of rural households, which could increase the affordability to pay the electricity and appliances price.

The GoC has implemented different energy efficiency measures through the non-conventional energy resources and Energy Efficiency Fund (FENOGE) created in 2017. One of these initiatives is the Caribbean Energy Sustainable Energy Efficiency Program (PEECES in Spanish) which seeks to benefit low-income families from the departments of Atlantico, Bolivar, and Cordoba through an incentive of about €100 on the total value of the new and more efficient refrigerator. In return have to deliver their old refrigerator for environmentally proper final disposal (FENOGE, 2020).

In the off-grid market, public funds have focused on financing the installation of stand-alone solar PV kits (i.e. solar panels, inverter, charge controller, battery, wiring systems, and electrical cabinet) with an average installed capacity of about 750 Wp (CREG, 2020a). These systems guarantee that off-grid populations can access enough energy for lighting, home cooling, refrigeration, entertainment (e.g. mobile phone charging), and cooking. Between 2018 and 2021, the GoC installed 26,831 systems throughout the country, including La Guajira, with 1.633 systems under operation. However, the provision of electrical appliances such as efficient refrigerators, TVs, or fans, is not included in these kits. Thus, additional initiatives are required to promote the use of efficient appliances that are appropriate for off-grid and weak-grid markets, such as La Guajira. This includes providing incentives to local service providers to offer more efficient solutions for lighting and other basic energy services, which could lower the monthly electricity demand of rural households, and thus, the government of Colombia could install smaller off-grid systems that require a lower CAPEX. This could incentivise the efficient use of public funds in the off-grid areas of Colombia.

For instance, considering an energy-efficient policy where 100 W incandescent light bulbs are replaced by 15 W compact fluorescent lamps (CFLs) and also, that high-performing refrigerators of 200L are available and require an average power of 80-100 W, the monthly electricity consumption of rural households in La Guajira can be reduced in about 58%, as presented in Table 9.8.

Table 9.8 Energy Efficiency (EE) impact on households' energy consumption

Subregion	**Monthly electricity consumption (Base case) [kWh]**	**Monthly electricity consumption (EE Policy) [kWh]**	**Electricity demand savings (%)**
Upper Guajira	142.4	**47.16**	-66.9%
Middle Guajira	171.8	**76.19**	-55.6%
Southern Guajira	179.9	**84.29**	-53.1%
		Total average	-58.6%

Therefore, as off-grid appliances become more efficient, supply and demand-side constraints are alleviated. From the supply-side, future levels of appliance ownership could incentivise future market businesses: SHS and minigrid providers could be able to power a far wider range of appliances, and electricity access could be enhanced. In addition, estimating the expected customer demand is useful in identifying customers that are likely to consume enough electricity to justify the cost of connecting them. From the demand-side switching to energy-efficient appliances could reduce energy consumption for less money.

9.4. Chapter Summary

Results indicate that hybrid minigrids represent a potential alternative to decarbonise the off-grid sector and improve electricity access. However, there are still key concerns related to this technology solution.

Overall, this chapter has analysed the case of La Guajira, Colombia, to understand consumer demand and preferences for off-grid appliances and to develop estimates of electricity-consuming appliance ownership. Using cross-sectional data from 1,255 rural households, the appliances driving the monthly electricity consumption were identified. Then, an econometric diffusion analysis was implemented to explore the influence of socio-economic factors (i.e. income, electricity access rate, and percentage of rural population) on the ownership of selected appliances. Results confirm the need to implement energy efficiency measures for specific appliances to maintain levels of energy demand, which could impact companies' revenues, and thus, electrification investments could grow within the unelectrified off-grid areas. Finally, this study estimates the electricity demand savings when energy efficiency improvements are incorporated into selected appliances. Results indicate that TVs are the most used devices in about 70% of rural households of La Guajira, followed by blenders, fans, and refrigerators. In particular, the level of electricity access and the index of rurality of the community show the highest statistical significance and collectively explain 91% variance in refrigerator ownership. Also, replacing current inefficient light bulbs and refrigerators with high-performing appliances could reduce the monthly electricity consumption of rural households in La Guajira by about 58%. These findings provide evidence of the size of the addressable market for off-grid appliances in La Guajira and the need to implement energy efficiency measures for specific appliances.

10. Conclusions: Policy implications towards reaching the last mile

This chapter summarizes the research results and the main conclusions drawn from the research questions. This thesis concluded that Colombia's rural electrification efforts are not enough to achieve universal access. Both, qualitative and quantitative research methods have been established to identify the main challenges affecting the electricity service expansion to last-mile communities. In this regard, a set of policy recommendations for tackling the identified challenges are proposed, including the definition of better-designed electricity tariffs and subsidy schemes; improving access to finance to private companies; fostering concession agreements through long-term contracts; setting a legal reform that guarantees the subsidies allocation within the service provision contract; and promoting the community participation throughout the project implementation. Reaching the last-mile communities with long-term sustainable projects, not only requires an integrated energy planning but also, effective coordination between different stakeholders. In addition, limitations identified in addressing the research questions and potential future research topics are identified.

10.1. Meeting the objectives and answering the research questions

> *Main Objective: Demonstrate the validity and limitations of different methods to support rural electrification planning in developing countries.*
>
> *Research Question 1: Are current electrification programs reaching the poorest rural households?*

The main findings of chapter 6 respond to research question 1. They indicate that prioritising electricity service expansion based on the unsatisfied basic needs (UBN) index represents a valid criterion to achieve the largest gains in electricity access for the poorest communities. Using another type of poverty measurement, such as the HDI, could have resulted in prioritising other areas.

In particular, it has identified the government of Bolivia's criteria for prioritising areas for electrification and analysed the suitability of using the UBN index as a social criterion for this purpose. In doing so, it was explored whether electrification programs such as the PEVD are reaching the poorest communities in urban and rural areas.

Results suggest that the level of poverty (measured by the number of unsatisfied basic needs) of potential communities is considered one of the criteria to select priority areas, regardless of the technology option chosen. However, other aspects such as the population density receive a higher score (i.e. for the grid extension option), as extending the grid requires a relatively concentrated population to be electrified. So far, the PEVD has prioritised not only the poorest communities but also those municipalities with a population density above the national average. In consequence, in order to reach the last mile for universal access, future projects should focus on the areas of Potosi, Pando, and Beni, which were the poorest states by 2012 and where levels of electricity access continue below 90% (as of 2018).

In addition, results indicate a positive association between the 2001 UBN index and the improvement in the electrification rate between 2001 and 2012. These findings imply that if electricity access is provided to those with a high UBN index, a significant improvement in electricity access can be achieved, especially in remote and scattered rural areas, where extending the grid is not economically viable. In fact, based on the percentage of the UBN poor in Bolivia (as of 2001), the highest improvement (by 2012) was achieved in municipalities with the highest UBN indices rather than those with the highest deficits in electricity access.

However, this study has a few limitations worth discussing here. Most importantly, the dataset is based on the national censuses of 2001 and 2012, corresponding to the years with available information about the UBN index. Future estimation of this index will be released from the next census, expected to be conducted by 2021. Besides, estimating poverty rates through the UBN index also depends on access to water, sanitation, education, and health. Unfortunately, poor people are prone to experience multiple deprivations at the same time. This means that someone who falls short in one indicator of well-being (e.g electricity access) is quite likely to fall short also in another indicator (such as education). Also, disparities between urban and rural areas continue to prevail. As a result, an area in which most people are deprived of education requires a different poverty reduction strategy from an area in which most people are deprived of housing conditions. In consequence, focusing on one factor alone, such as the electricity access rate, is not enough to capture the true reality of poverty.

In Colombia, the UBN index is not considered to prioritise off-grid projects, namely, through the FAZNI, as presented in Table 6.2. One explanation is related to the homogeneity in the level of poverty in the off-grid areas. Thus, using the UBN index does not necessarily offer distinctive information to prioritise where to carry out electrification programs in these remote rural areas. In consequence, including the MPI in the FAZNI prioritisation approach could contribute to targeting the poorest areas. In particular, the MPI goes beyond the traditional UBN indicators by including deprivations in employment and social protection as well as the schooling gap. In addition, the MPI is already being used as a public policy tool in the Colombian context to track deprivations across the country, monitor public policies by sector, and design the poverty reduction goals of the National Development Plan (Salazar et al., 2013).

For energy access researchers and policymakers, these general findings may offer some direction for future research. First, these results could help Bolivia in prioritising future electrification programs. In particular, the country is on the verge of beginning Stage IV (2020–2025) of the PEVD program, and using the UBN index could contribute to prioritise the poorest communities who still do not have access to electricity. Second, they provide evidence of how other developing countries could identify and prioritise geographical areas for the provision of electricity access, accounting for the type of electricity supply technology.

Research Question 2: What are the key challenges and main drivers of risk in off-grid electrification projects?

Chapter 5 presented a summary of different challenges (including a set of technical, social/cultural, policy/regulatory, and financial/economic aspects) regarding the provision of electricity in off-grid areas of Colombia, especially to achieve the last-mile communities. Unfortunately, most un-electrified areas in Colombia are far away from the SIN and correspond to areas with less dense populations and lower demand, and thus key hurdles continue to prevail.

One critical barrier is the limited public funds to implement energy access projects and the lack of private investments in the rural electrification sector. So far, since the publication of the PIEC until August 31, 2021, nearly 59,166 new households have gained access to electricity through stand-alone PV systems or with grid interconnection (MME, 2021a). Additionally, by 2022, it is expected to provide electricity service to about 57,000 new households. Based on this progress, 379,633 households (out of 495,799 as of 2018), or nearly 1.5 million people will still lack access to electricity by 2023. This number suggests that to achieve universal access by 2030, investments should focus on providing electricity to nearly 47,000 households per year, between 2023 and 2030, which requires a total investment of nearly €254 million-an amount far greater than the funds collected by FAZNI and FAER. However, this projection does not quantify the COVID-19 pandemic which has threatened the electrification progress by increasing investors' risk perception and shifting public funding priorities in developing countries (IEA et al., 2021). Also, public funds allocated to expand coverage in the ZNI (i.e. the FAZNI, FAER, FNR, FENOGE, and the FPTSP) are insufficient to achieve universal coverage within eight years if new requirements arising from population growth and the current post-conflict stage are also considered. Thus, as public financing may remain limited over the next few years, it is critical to unlock and promote private financing in the rural electrification sector.

Alternatives with the possibility of private investment not only can increase financial sustainability for off-grid systems but also brings financial competitiveness and reduces inefficiency and corruption. However, the lack of clear public policies, together with a high perceived risk, has been a deterrent to investors' participation in off-grid electrification projects.

As presented in Chapter 8, this thesis studies the perceived uncertainties and resulting risks that prevent private companies to invest in the off-grid electrification sector of Colombia. By combining the heat map method with stochastic techniques, scientific data was visualized and analysed. As a result, as presented in Table 8.1, 12 out of the 16 types of potential risks correspond to Business Risks. The variability in revenues corresponds to the main source of Business Risk and the main concern of potential investors. In particular, the variability in Annual Revenues and the Annual revenue growth rate are the most impactful variables to the variability of the project's NPV. In addition, Business Risks represent the most relevant risk that might be affecting the company and the outcome of its project financials. This type of risk comes primarily from the uncertainty of the project revenues and the expected cost of operations. In this case, the results suggest that the current electricity tariff is not able to cover the operational costs required for this project.

Despite there are some uncertainties and risks that require further examination from potential private investors, this study confirms that solar PV projects with stand-alone systems represent a cost-effective solution to expand electricity access. Using the technical, economic, and financial assumptions of the Colombian case study, results show that the selected project justifies investment from private companies (i.e. NPV >0), assuming a subsidy allocation on the CAPEX and OPEX of the system. Also, when examining the risk of project failure through the value at risk or VaR of the project, findings show that the probability that the NPV is less than zero is about 4.9%, thus, private investors could mitigate the existing risks through their business model.

Research Question 3: Which factors determine the long-term sustainability of off-grid electrification projects in rural and remote communities?

In Chapter 7, the summary analysis of the results indicates that selecting the most appropriate site for implementing off-grid solar PV projects, is one of the key decisions that private investors face within the rural electrification sector. Overall, scaling up sustainable RE systems (such as stand-alone systems and minigrids) in the rural electrification sector requires accounting on key dimensions, namely the social/cultural, technical, financial/economic, and policy/institutional perspectives that guarantee the long-term sustainability of these projects and involving multi-stakeholder partnerships, as presented in Figure 1.5. As presented in Akinyele et al. (2018), *"all the dimensions need to work together to overcome the barrier and achieve the desired sustainable energy development, which is beyond the traditional techno-economic planning perspective"* (p. 4).

In addition, the definition of sustainable rural electrification programs and policy guidelines depends on considering the point of view of different stakeholders, such as utility companies, providers, academia, and the public sector. Having each sector's insights creates a collaborative visualisation and understanding of the regulatory, financial, economic, environmental, social, and technical needs to guarantee the long-term sustainability of off-grid projects, regardless of the type of technology. This strategy should be attached to a long-term sustainable energy planning framework that not only provides a pathway towards achieving universal access but also indicates the areas in which electrification efforts should be prioritised, including the three modes of electrification (i.e. grid extension, stand-alone systems, and minigrids). This plan also should integrate indicative measures to foster the replacement of predominant diesel-powered plants installed in the ZNI with more efficient energy technologies.

In Chapter 7, a MCDM method was implemented to select the most sustainable option to develop a solar PV off-grid project, accounting for key sustainability criteria based. In particular, 13 criteria were categorised within 5 dimensions: technical, social, commercial, economic, and environmental, based on the private sector's perspective. Through analysing the three options with the MACBETH approach and software, results indicate that Colombia and Peru are the most sustainable alternatives based on their associated global score (98.23% and 71.56%, respectively). The number of *Potential off-grid households* was the criterion with the highest influence on this evaluation model, with a weight of 18.47%. In addition, the Economic and Commercial dimensions had a direct influence (in about 88%) on the decision-making of selecting the most appropriate off-grid location to implement stand-alone solar PV off-grid projects.

Particular attention is given to the technical dimension in Chapter 9. Results indicate that off-grid hybrid microgrids with renewable energy are a feasible alternative to reducing the need for diesel generators in off-grid areas of Colombia, in terms of the LCOE. Hybrid minigrids have the potential to increase the quality of power supply and enable productive uses of electricity, by providing reliable service to off-grid communities for 24 hours. Also, they contribute to diversifying the current energy matrix in the off-grid areas of Colombia by integrating renewable generation, allowing the country to reduce GHG emissions. Additionally, promoting a clean energy value chain can reduce the government's diesel subsidies. Currently, subsidies to users served by diesel-based generation systems in non-interconnected zones are about 10 times higher than the subsidies granted to users served by the interconnected national system. The higher subsidies are due to the high transportation costs of supplying diesel to isolated zones. By reducing these subsidies, the Government will be able to reallocate funding to poverty alleviation initiatives.

However, there are still key concerns related to this technology solution, including a lack of detailed information and awareness on where diesel minigrids are located and the level of feasibility (technical and financial) of converting diesel minigrids to low-carbon systems; a high-risk perception towards novel low-carbon minigrid projects; a lack of a clear regulatory tariff for private investors interested in implementing minigrid projects in the ZNI. The current tariff corresponds to CREG Resolution No. 166-2020, a transitory scheme that estimates the maximum monthly tariff for providing electricity service in off-grid areas (COP$/month), through stand-alone solar PV systems (> 500 Wp, AC) (CREG, 2020a). Instead, minigrid developers need to request the approval of a monthly tariff from the CREG and this process can last between six and nine months. Finally, potential investors face a lack of capital and limited access to finance the large-scale development of minigrids.

Thus, effective policy interventions are required to foster Colombia's transition to low-carbon minigrids in off-grid areas, including derisking measures that guarantee the policy and financial security to potential minigrid private developers (private investors).

Research Question 4: To what extent are current rural electrification policy measures and interventions supportive of promoting sustainable rural electrification planning?

Bolivia, Colombia, and Peru have shown commitment to achieving universal energy access, by adopting the SDG7 of the UN (United Nations Statistics Division, 2021). As presented in Table 4.1, Table 4.3, Table 5.2, and Table 5.3, these countries have set national programs, plans, public funds, and strategies for the achievement of the SDG 7.1. In the three countries, the main policies for rural electrification have focused on expanding the electricity grid, integrating renewable energy in off-grid projects, and providing subsidies to low-income rural households. For instance, between 2018 and 2022, the Government of Colombia expanded the electricity service to nearly 90,000 families though public funds (~US $350M), achieving 90% of the goal set in the 2018-2022 Colombia's National Development plan (MME, 2022b). Peru's Rural Electrification Program has been effective in promoting the use of off-grid solar systems for providing electricity to remote areas (See Table).

In addition, these countries have called for additional financing through multi-lateral banks such as the WB, the IDB, the NDF, and the KfW to support the implementation of massive rural electrification programs. For instance, in Bolivia, the IDB has financed about US$160M for the implementation of the Rural Electrification Program (PER in Spanish)- phase I and II- benefiting more than 30.000 with new access to electricity mainly through the grid extension and through off-grid RE based solutions for the most remote households (BID, 2020, 2017).

However, additional efforts are required to achieve the last-mile communities, including greater investment in infrastructure and ensuring affordability of the energy service. Currently, a total of 3.3 million people live without access to electricity in these three countries (as of 2021) (OLADE, 2022). Special attention should focus on effective rural electrification planning that integrates innovative methods such as the integration of geospatial information within the selection of the optimal energy technology solution to be installed at each off-grid household. Also, lessons from previously implemented rural electrification plans should be considered in future interventions.

10.2. Insights for Policymakers

This thesis highlights the need for integrating private investment into the rural electrification sector. In this section, I present a set of policy recommendations to mitigate the most potential risks affecting the private sector participation in off-grid electrification projects, using the case of Colombia. These measures are indicative, and they may require a collaborative effort between the public entities and the private sector.

Reducing the private sector's uncertainty about where to implement off-grid rural and remote electrification projects requires accounting not only for local conditions, technical constraints, and economic-financial feasibility but also for socio-cultural dynamics and environmental consequences (Rahman et al., 2013). Within this context, multi-criteria sustainability assessments could guide off-grid developers seeking to select the most appropriate locations (based on key dimensions of sustainability) to implement off-grid solar PV projects, as presented in Hinestroza et al., (Hinestroza et al., 2021) where authors implemented a multi-criteria model to assess the suitability of potential sites to implement off-grid Solar PV projects, using the case of Bolivia, Colombia, and Perú.

Table 10.1 presents indicative recommendations that could contribute to mitigating the uncertainties and perceived risks highlighted in this thesis (See Chapter 8). Each potential measure is categorised within a multidimensional perspective for achieving sustainable energy planning in off-grid rural communities. It accounts not only for technical constraints, and economic-financial feasibility but also for socio-cultural dynamics, environmental consequences, and policy/regulatory interventions of rural electrification projects. In addition, the potential intervention of key actors is linked to each measure.

Table 10.1 Indicative policy guidelines to address uncertainties and mitigate resulting risks in RE off-grid projects.

Sustainability dimension	Guidelines	Key actor
Financial/ Economic	• *Customer churn rate*. Implement sales strategies with local shopkeepers willing to sell the service to end-users. • Adapt business model to end-users' income (e.g. Pay-as-you-go models) to reduce revenue uncertainty. • *Demand risk*. Estimate revenues under different scenarios for the demand forecast of the community. • Retain local sales managers by providing incentives such as per-sale commission. • Promote effective revenue collection mechanisms. • Implement customer service (i.e. call-centre to report any fault or repair required) to foster customer ownership. • *Sources of capital investment*. Build strategic partnerships with investors and/or seek donor support through non-reimbursable credits.	Priv. Priv. Priv. Priv. Pub; Priv. Priv. Priv.
Technical	• Conduct market research and draw from existing operating projects to reduce uncertainty about the cost structure of the project. • Provide reliable information about the communities' socio-economic and GIS characteristics (i.e. location coordinates, payment capacity, culture, economic activity, level of poverty, and level of literacy, among other aspects). • *Technical failure of components*. Improve equipment reliability and efficiency (i.e. minimise maintenance visits). • Set clear and consistent government technical requirements for the RE system's design and configuration in off-grid areas. • Reinforce the adoption of energy certificates.	Priv. Pub. Priv. Pub. Pub.
Social/ Cultural	• ***Community acceptance/awareness.*** Conduct talks and workshops to educate end-users on the products and payment terms and operations (i.e. awareness programs). Also, to socialise the community's energy needs and culture. • Involve the community throughout all the phases of the project. • *Ability and willingness to pay*. Conduct market research, through surveys or interviews, to gather information about the communities 'current energy access and expenditures; aspirational energy needs; economic activities; and ability to pay for the electricity service. • *Skilled personnel (for O&M activities)*. Implement capacity-building programs to build and grow teams in a scarce talent environment (i.e. foster technical assistance programs to retain trained and skilled staff). • *Theft of components/system*. Employ local personnel and manpower. Also, integrate innovative systems with secure lock authentications. • Enable prepaid energy using innovative and robust technology.	Pub; Priv. Pub; Priv. Pub; Priv. Priv. Priv. Pub; Priv.
Policy/ Regulatory	• *Subsidies redefinition*. Define flexible subsidies that adapt to the communities' economic conditions but also that guarantee the projects' expected return on investment. • *Electricity tariff*. Set electricity tariffs that adapt to the off-grid community's conditions and guarantee that private investors will cover their operating expenses from revenues (i.e. electricity sales) • Tariff variability adjusted to the technology option. • *Incentives provided by the government*. Design new incentives derived from international best practices examples. • Improve access to finance through attractive DFI financing opportunities. • *Long-term planning mechanisms*. Promote new mechanisms that integrate long-term contracts for the energy provision in rural and remote areas (e.g. rural concessions). • *Reduce private sector risk perception*. Enable new financing programs (i.e. long-term finance to address payback) with enough legal security. • Implement training on RE projects in financial institutions and other Ministries. • Enable access to international funds to finance off-grid projects.	Pub.

*Pub. stands for Public sector and Priv. for Private sector

As presented in Chapter 8, the uncertainty of revenues resulted to be the most critical variable influencing the expected value of NPV, as illustrated in Table 8.1. Off-grid service providers have low debt capacity due to unpredictable revenues from customers with non-recurring incomes. Thus, policy guidelines could include setting proper electricity tariffs that adapt to communities' economic conditions, depending on the local socio-economic conditions of the area where the project will be implemented. It requires accounting for the logistics, transportation, and other operating costs that service providers expect to recover on revenues (i.e. tariffs and subsidies). In addition, new tariff schemes are required to address the treatment of OPEX for different technologies, such as hybrid minigrids. In this context, governments play a key role, because the long-term sustainability of the projects mainly depends on the OPEX subsidies. These incentives are necessary to cover part of the high upfront O&M costs and thus, achieve competitive returns on the investment. Also, private investors require the legal guarantee that subsidy allocation will continue despite the change of government during the service provision contract.

Addressing potential business risks derived from the revenues uncertainties also depends on fostering community participation and inclusion in the planning, implementation, and maintenance of the projects. This action not only promotes community awareness of RE systems but also reduces misinformation/perceptions about the project. Dialogue and participation are the best strategies for community support for the project. For instance, in the structuring phase of the projects financed with the FAZNI, communities participate by identifying main energy needs (i.e. requirements in domestic comfort, education, and lighting, among others), the presence of ethnic groups, and/or georeferencing the neighbours. For this purpose, qualitative techniques such as social maps and sociocultural surveys are used. With these instruments, it is possible to define the profile of the communities and thus, structure the project. Then, during the project implementation, some strategies could include conducting talks, and technical training programs to educate end-users on the system technology, the rational use of energy, the revenue collection scheme, the tariff scheme, and the maintenance activities they could perform, such as cleaning the solar panel glass.

Another important issue affecting the company's revenues is the percentage of inactive or lost customers, namely the customer churn rate (CCR). This study assumes a CCR of zero, but normally, off-grid service providers work to maintain a low CCR. One alternative to maintaining a low CCR could imply implementing business models with flexible payment options that adapt to the end-user's income variability, such as the pay-as-you-go service, in which the customer makes payments (via a mobile money platform) to buy credit for activating (i.e. turning on) the generation system in a daily, weekly or monthly basis. Local sales managers could play a key role in promoting these payments within the community, and in return, they could obtain a per-sale commission.

Also, employing local personnel contributes to increasing sales, since they sustain customer relations, by speaking the same language (i.e. in indigenous communities), sharing the same culture, and having a more complete understanding of how these homes operate. However, these sales agents require consistent attention and training, as well as the technical staff. Thus, additional investment is required to cover the costs of designing, implementing, and monitoring the training program, including hiring technical staff for teaching, transportation, and travel expenses to the communities.

One strategy for reducing the uncertainty about the cost structure of the project is fostering an adequate estimation of the operating and maintenance costs (i.e. fixed and variable costs). For instance, defining the required number of technical visits to provide preventive maintenance to each system is essential because it impacts the amount of technical skilled staff required for the operation and maintenance of the system. Unfortunately, in these remote and rural areas finding these specialised personnel represents a major barrier. Therefore, projects should account for investing in training programs to promote local employment and guarantee the technical and commercial sustainability of the project. Measures to mitigate thefts and vandalism should focus on promoting innovative security systems that reduce the probability of hacking, energy theft, or selling the system, thus ensuring the success of the implemented business model. In addition, companies could lower their operating costs by having reliable equipment out in the field which minimises the maintenance the technical staff needs to provide to each system. Based on the interviewees' experience, keeping the costs of operation low is critical. They suggest that operating costs at scale should be less than 50% of revenues as companies can spread fixed costs over a larger revenue base.

Under this scenario, development finance institutions (DFI) also play an important role in financing private sector investments in rural electrification projects, in the form of higher-risk loans, equity, guarantees, and debt securities (Willem and Warner, 2007). The financial market has the potential to offer reasonable long-term financing to sustain the project and achieve a reasonable payback period. Thus, the government could foster programs to provide financial support to investors through on-lending to DFI. This could result in DFI becoming more familiar with RE technologies, hence reducing their risk perception and, over time, increasing their supply of financing for this type of project. For instance, the IDB Invest, a member of the IDB Group has financed sustainable companies and projects to achieve financial results and maximise economic, social, and environmental development in the region of LAC through the private sector. Transactions include blended finance equity investment that provides value-added patient capital to help companies secure the additional investment required to scale up operations within a market (IDB Iinvest, 2020).

As presented in IDB (2015), some experiences in developing countries have shown the need for non-reimbursable funds varying from 40% to 60% of the initial investment (IDB, 2015). In Bolivia, Colombia, and Peru, the IDB has been an important partner by offering equity and debt for private or public-private projects. However, a potential source of risk could derive from the need for additional investment to replace spare parts or assets, such as the battery system at the end of its life cycle, representing about 40% of the system cost (See (CREG, 2020b)) but required in the current Build, Operate, Maintain and Transfer (BOMT) contracts. Thus, setting appropriate subsidies to cover O&M is also critical.

Finally, awarding long-term concessions within rural areas of the country can be an effective mechanism for addressing business risks and promoting economies of scale in rural electrification projects. In 2019, the GoC, through the MME, conformed to an expert mission to propose adjustments aimed at promoting an energy policy based on an energy transition scheme (Ortiz Jara et al., 2020). Within the recommendations associated with Focus No.4 "Closing gaps, improving quality and efficient design and formulation of subsidies", the mission recommended analysing the concession model to provide electricity coverage in the last-mile regions. Under this scheme, the GoC could implement an auction in which companies bid for areas of responsibility in the ZNI (MME, 2021b). Following this recommendation, the MME and IPSE have designed a rural electrification program that includes a series of incentives that promote the provision of private capital under a long-term contract in assigned areas of the ZNI (IPSE, 2021d). The main purpose is to grant several areas to private companies willing to provide electricity service, including the O&M activities in a long-term contract (IPSE, 2021e). Aligned with this recommendation, a scalable business model will require an attractive and commercially viable proposition, namely a public-private hybrid model where the public entity supports off-grid electrification development.

These results are of interest to private investors who need to account for risk analysis when deciding whether to invest or not in off-grid projects. Also, these findings could guide policymakers seeking to understand the private sector perspective while designing efficient policy mechanisms to increase access to electricity in developing countries. Although the proposed policy measures are country-specific, this analysis can be potentially used as a reference for private companies facing decision-making investment problems in off-grid areas of other developing countries, especially in LAC.

10.3. Future Research

Potential trajectories for future research could address the following topics:

10.3.1. Energy demand modelling

Private companies require accounting for reliable information about the level of energy consumption of newly electrified communities. This data is not always available and increases the risk perception of potential investors looking for customers who consume enough electricity to guarantee the company's revenues. In Chapter 9, results provided evidence of the size of the addressable market for off-grid appliances in La Guajira, Colombia, and the need to implement energy efficiency measures for specific appliances, namely refrigerators, and fans. However, future research could focus on analysing the relationship between other reported appliance ownership (e.g. television, radio, telephone, or mobile phone) and electricity access. Results could provide evidence of the size of the addressable market for off-grid appliances, by understanding consumer demand and preferences for off-grid products and exploring opportunities that can catalyse growth in rural areas. This analysis could be replicated in other off-grid areas.

10.3.2. Techno-economic assessment of hybrid minigrids in off-grid areas

Chapter 9 highlighted the need to promote the implementation of low-carbon minigrids. In this case, a techno-economic comparison model that determined the optimal electricity supply technology for a certain location, based on the Levelised cost of energy (LCOE) was applied. However, additional technical studies could focus on analysing key concerns related to this technology solution. For instance, due to the intermittent nature of renewable power, minigrids either require a large storage system or suffer from a lack of reliability. Given these circumstances, minigrids today are often not cost-competitive with centralized power generation, and they face the risk of becoming an abandoned infrastructure when the national utility arrives. One alternative to address inefficiencies in minigrids is allowing the interconnection of neighbouring islanded minigrids. Thus, future research could focus on evaluating the technical and economic benefits of interconnecting rural minigrids to guarantee the level of security of each microgrid. This implies performing a contingency analysis, using the N-1 criterion to assess each system's response to withstand at all times an unexpected failure or outage of a single system component. This analysis could reduce policy and financial uncertainty for minigrids developers, considering that according to the PIEC 2019-2023, nearly 48% of the investment required to achieve universal access will focus on minigrids projects.

10.3.3. Off-grid business models and financing mechanisms: public and private partnerships

During the last decades, various approaches to increasing the flow of private investment to rural electrification have been attempted, since public funds alone are insufficient to meet the goal of achieving universal access. Governments from developing countries facing electricity access deficits have recognised the need to implement alternative institutional and business models to speed electrification. Within this context, a common answer is to bridge the financing gap by leveraging the resources of the private sector through "public-private partnerships" (or PPP). PPP represent a means to attract foreign direct investment, procure financing from private lenders, and thus, guaranteeing the electrification projects' long-term sustainability. In addition, there is a need for analysing the potential of providing long-term contracts (e.g.> 15 years) to energy service providers, through concessions that guarantee the sustained operation and maintenance of RE electrification projects. The case of Peru offers key lessons in this matter.

10.3.4. Definition of a least-cost integrated energy planning based on Georeferenced Information Systems (GIS)

Local governments are increasing efforts to identify the location of off-grid users at the country level based on Geographic Information Systems (GIS). These countries could benefit from the formulation of a georeferenced rural electrification plan, optimized at the lowest cost, by identifying both the energy solutions to be implemented throughout the country and the associated investments that will allow achieving universal access to energy by 2030. It will also provide support to developing a georeferenced database in GIS format with relevant information for the development and monitoring of the plan, including a set of minimum technical specifications for projects resulting from the national electrification plan.

10.3.5. Impact evaluation of RE projects

There is a need for investing in impact evaluation of electricity access studies that provide evidence for the socioeconomic impacts of electricity access. In particular, research on how energy access interventions are effective to bring the intended benefits of improving living conditions of rural communities. This requires a systematic review of impact evaluation methods, data analysis of already implemented projects, and conduct statistical analysis that justifies the replication of off-grid electrification projects.

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Appendices

Appendix A

Referenced Data Source in Chapter 3

Encuesta de Consumos y Usos de Energía
Sector Residencial

kingo

Buenos días, tardes, mi nombre es_________________. En este momento estamos realizando un estudio sobre usos y consumo de energía en el sector rural del departamento de La Guajira. Estamos solicitando su colaboración con esta encuesta donde sus respuestas tendrán un tratamiento confidencial y serán utilizadas con fines estadísticos y académicos para la empresa

Fecha Encuesta — Día ____ Mes ____

Municipio: ____

Nombre de la localidad: ____

Registro Fotográfico ☐

1. IDENTIFICACIÓN DE LA VIVIENDA

1. Nombre de la persona que contesta la encuesta

Rol: ____

2. Ubicación de la vivienda

Cabecera Municipal ☐ Caserío ☐ Otro ☐
Corregimiento ☐ Vereda ☐

3. Tipo de usuario:

Cliente ☐ Potencial Usuario ☐
Tendero ☐

2. MÓDULO COMPOSICIÓN FAMILIAR

4. Cuántas personas componen el hogar? ____

No.	Edad	F/M	Escolaridad: Ninguno	Preescolar	B. Primaria	B. Secundaria	B. Media	Superior
	0-6							
	7-12							
	13-18							
	19-26							
	27-59							
	59+							

3. MÓDULO ECONOMÍA FAMILIAR

5. Actividades principales que generan ingresos

6. ¿Cuáles son los gastos familiares al mes ?

	COP $
Alimentación	
Educación	
Servicios	
Transporte	
Otros	

4. MÓDULO SOCIOCULTURAL

7. ¿Quiénes realizan las siguientes labores (Niños/Niñas/Mujeres/Hombres)?

Labores Domésticas	
En mayor medida pagos y compras de la canasta familiar	
Labores finca	
Recolección Leña	
Recolección Agua	
Transporte	
Estudia	
Comercia	
Formación Hijos	
Cuidado animales	
Otros	

5. MÓDULO ENERGÍA

8. ¿Cuánto tiempo demora cocinando al día? ____

9. ¿Qué usa para iluminarse?

Leña ☐
Lámpara de Gas Propano ☐
Lámpara de Kerosene o petróleo ☐
Lámpara de Gasolina ☐
Velas ☐
Pilas o baterías ☐

10. ¿Qué tipo de electrodomésticos tiene o quiere/necesita?

	Tiene	Quiere
Ventilador		
Radio		
Bombillo cocina		
Bombillo sala		
Bombillo baño		
Bombillo Patio		
Nevera		
Celular		
Equipo sonido		
Otro		

11. ¿Qué tipo de servicio Kingo tiene?

Kingo Básico ☐ Otro ☐ ____
Kingo Luz ☐
Kingo TV ☐
Kingo 100 ☐

12. ¿Conoce los diferentes productos/servicios que ofrece Kingo?

Sí ____ No ____

13. ¿Cuánto estaría dispuesto a pagar mensualmente por un Kingo de mayor capacidad?

Kingo Luz ____
Kingo TV ____
Kingo 100 ____

14. Indique principiales dificultades que ha tenido utilizando su Kingo:

Requiere más de una hora para llegar al tendero más cercano ☐
Dificultad para recordar códigos de uso del Kingo ☐
Robo de equipos en la zona ☐
El equipo ha dejado de funcionar varias veces ☐
Otro ____

¡Muchas gracias por su tiempo!

Figure A1. Survey template to collect information from local communities in La Guajira, in 2020.

Appendix B

Structuring the Evaluation Model

Table B1. Constructed performance scale for each criterion

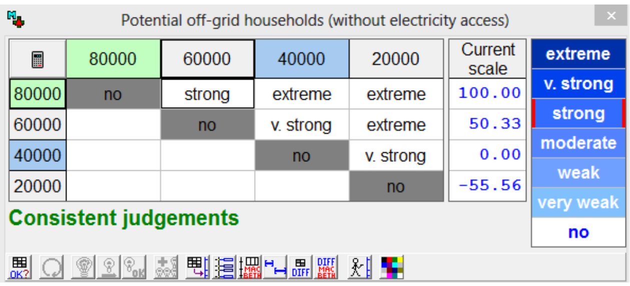
Dimension	Criteria	Unit of the descriptor	Type and Performance Scale
(E) Economic	(E1) 2018-GDP per capita	US $	Four-level *quantitative* scale ranging from US $3,000 to US $6,000
	(E2) 2013-2018 Average GDP growth- 5 years	%	Four-level *quantitative* scale ranging from 3% to 9%
	(E3) 2018 Poverty Index (PL)	%	Four-level *quantitative* scale ranging from 10% to 40%
	(E4) 2018 Financial Inclusion	%	Four-level *quantitative* scale ranging from 50% to 80%
(C) Commercial	(C1) Potential off-grid households (without electricity access)	households	Four-level *quantitative* scale ranging from 20,000 to 80,000
	(C2) Dispersion index (potential off-grid households/area)	number of households/km²	Three-level *quantitative* scale ranging from 0.1 to 1
	(C3) 2018 Rural Mobile phone ownership	%	Four-level *quantitative* scale ranging from 40% to 70%
	(C4) Solar PV Investment-National rural electrification plan	US $M	Four-level *quantitative* scale ranging from US $0M to US $600M
(T) Technical	(T1) Solar potential	kWh/m²	Four-level *qualitative* scale: Very High Potential: 4.5-5 kwh/m² High Potential: 4-4.5 kwh/m² Medium Potential: 3.5-4 kwh/m² Low Potential: <3.5 kWh/m²
(Env) Environmental	(Env1) Extension Protected Areas	%	Four-level *quantitative* scale ranging from 0% to 15%
	(Env2) Average terrain elevation	m.a.s.l.	Four-level *quantitative* scale ranging from 50 to 110
(S) Social	(S1) Rural Illiteracy rate	%	Four-level *quantitative* scale ranging from 5% to 15%
	(S2) Security Level (Global Peace Index)	points	Five-level *quantitative* scale ranging from 0 to 8

Table B2. Performance Profile of the Options (M-MACBETH software).

Table of performances

Options	GDPcap	GDPg	Poverty	FInc	PHouseholds_woEA	Dispersion	MPhone_rur%	SolarPV_inv	Solar_kwh/m2	PAreas	Elev	Edu	Security
PER	6941	3.26	20.5	80	148430	0.4	75	328866548	VHigh	16.93	235	14.6	6.8
BOL	3548	4.62	34.6	60	18664	0.29	53.1	357066229	VHigh	16	100	17.6	6.2
COL	6668	2.85	27	82	81960	3.93	87.5	413269543	VHigh	10.83	50	12.6	6.6

Table B3. Matrix of judgements for the "Potential off-grid households" criterion (M-MACBETH software)



Potential off-grid households (without electricity access)

	80000	60000	40000	20000	Current scale
80000	no	strong	extreme	extreme	100.00
60000		no	v. strong	extreme	50.33
40000			no	v. strong	0.00
20000				no	-55.56

Consistent judgements

extreme
v. strong
strong
moderate
weak
very weak
no

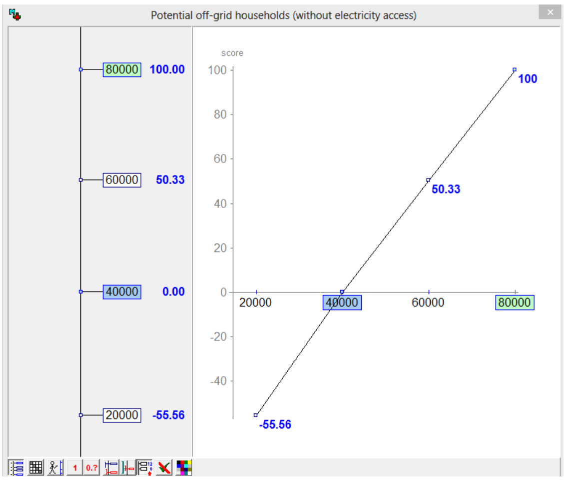


Figure B1. Value function for the "Potential off-grid households" criterion (M-MACBETH software)

Estimating the weighting coefficients- Simple weighting questionnaire

Instructions: Imagine an option exists that is neutral in every criterion:

1. How much would a swing from neutral to good in the *Potential off-grid households* increase its overall attractiveness?

	Extrem e		Very strong		Moderat e		Strong		Weak		Very weak		No

A similar question was subsequently asked for each of the other criteria, thus completing the last column of the judgements weighting matrix, as follows:

Table B3. Weighting matrix of judgements

Weighting (Off-grid Market Sustainability)

	[Flnc]	[SolarPV_inv]	[Security]	[Solar_kwh/m2]	[PAreas]	[Elev]	[NEUTRAL]
[PHouseholds_woEA]	?	?	?	?	?	?	extreme
[Dispersion]	?	?	?	?	?	?	extreme
[GDPg]	?	?	?	?	?	?	v. strong
[GDPcap]	?	?	?	?	?	?	v. strong
[Poverty]	?	?	?	?	?	?	v. strong
[MPhone_rur%]	?	?	?	?	?	?	v. strong
[Edu]	?	?	?	?	?	?	v. strong
[Flnc]	no	?	?	?	?	?	strong
[SolarPV_inv]	?	no	?	?	?	?	moderate
[Security]	?	?	no	?	?	?	moderate
[Solar_kwh/m2]	?	?	?	no	?	?	moderate
[PAreas]	?	?	?	?	no	?	weak
[Elev]	?	?	?	?	?	no	weak
[NEUTRAL]							no

extreme / v. strong / strong / moderate / weak / very weak / no

Consistent judgements

The next step was to elicit qualitative judgements from the decision-maker regarding the difference in attractiveness between swings. It began with the comparison of the most attractive swing to the second most attractive swing, by asking:

2. How much more attractive is a swing from neutral to good in *Potential off-grid households* than in *Dispersion Index*?

A similar comparison was subsequently made between the swing in *Potential off-grid households* and each of the other swings, thus completing (from left to right) the first row of the weighting matrix. This process was then repeated row-by-row, until the weighting matrix of judgements was completed. The consistency checks were automatically made each time a judgement was entered into the matrix. The MACBETH software then created the weighting scale for each criterion.

Table B4. Final weighing matrix of judgements and associated weighting scale

Weighting (Off-grid Market Sustainability)

	[Flnc]	[SolarPV_inv]	[Security]	[Solar_kwh/m2]	[PAreas]	[Elev]	[NEUTRAL]	Current scale
[PHouseholds_woEA]	v. strong	extreme	vstrg-extr	extreme	extreme	extreme	extreme	18.47
[Dispersion]	v. strong	v. strong	v. strong	v. strong	v. strong	v. strong	extreme	16.52
[GDPg]	v. strong	v. strong	v. strong	v. strong	v. strong	v. strong	v. strong	12.71
[GDPcap]	v. strong	v. strong	v. strong	v. strong	v. strong	v. strong	v. strong	12.71
[Poverty]	strong	v. strong	v. strong	v. strong	v. strong	v. strong	v. strong	11.52
[MPhone_rur%]	moderate	v. strong	v. strong	v. strong	v. strong	v. strong	v. strong	8.91
[Edu]	moderate	strong	strong	strong	strong	v. strong	v. strong	7.83
[Flnc]	no	moderate	moderate	strong	strong	strong	strong	5.22
[SolarPV_inv]		no	weak	weak	weak-mod	moderate	moderate	1.85
[Security]			no	weak	weak	weak	moderate	1.53
[Solar_kwh/m2]				no	weak	weak	moderate	1.20
[PAreas]					no	very weak	weak	0.87
[Elev]						no	weak	0.66
[NEUTRAL]							no	0.00

extreme / v. strong / strong / moderate / weak / very weak / no

Consistent judgements

Table B5. Table of rankings for each criterion

Table of rankings

GDPcap	GDPg	Poverty	Flnc	PHouseholds_woEA	Dispersion	MPhone_rur%	SolarPV_inv	Solar_kwh/m2	PAreas	Elev	Edu	Security
PER	7	20	COL	PER	COL	COL	COL	VHigh	0	50	5	0
COL	BOL	PER	80	COL	1	PER	400000000	PER	10	COL	10	4
6000	PER	COL	PER	80000	0.5	60	BOL	BOL	COL	BOL	COL	BOL
5000	3	30	60	40000	PER	BOL	PER	COL	BOL	110	PER	COL
BOL	COL	BOL	BOL	BOL	BOL	50	200000000	Med	PER	PER	BOL	PER

Appendix C

Estimates of the total costs[6] and revenues for the off-grid project under evaluation

Table C1. Comparison of annual costs and revenues (in US $) under three different electricity tariff scenarios and sizes of the project (number of users)*

Users	Costs			Revenues		
	Fixed	*Variable*	*Total*	*S1 (MET=US $31.77)*	*S2 (MET=US $54)*	*S3 (MET=US $73.41)*
401	$ 120,000	$ 130,246.6	$ 250,246.6	$ 152,877.2	$ 259,891.3	$ 353,268.4
624	$ 120,000	$ 202,678.0	$ 322,678.0	$ 237,893.8	$ 404,419.4	$ 549,724.4
689	$ 120,000	$ 223,790.3	$ 343,790.3	$ 262,674.4	$ 446,546.4	$ 606,987.4
890**	**$ 120,000**	**$ 289,075.9**	**$ 409,075.9**	**$ 339,303.6**	**$ 576,816.1**	**$ 784,062.1**
965	$ 120,000	$ 313,436.3	$ 433,436.3	$ 367,896.6	$ 625,424.2	$ 850,134.7
1252	$ 120,000	$ 406,655.1	$ 526,655.1	$ 477,312.5	$ 811,431.2	$ 1,102,972.7

* Assuming an exchange rate of US $1 = COP $3,700.
** Bold font indicates the data associated with the project under analysis.

Table C2. *NPV estimation for the selected project (in US $)*

Year (t)	**Free Cash Flow (FCF_t)**	**Discount Factor[b] $\frac{1}{(1+k)^t}$**	**Present Value of the cash flows occurring at year t $\frac{(FCF_t)}{(1+k)^t}$**
0	$ 480,600	1.00	$ 480,600
1	$ 168,031	0.91	$ 152,908
2	$ 167,937	0.83	$ 139,388
3	$ 167,187	0.76	$ 127,062
4	$ 167,865	0.69	$ 115,827
5[a]	-$ 543,792	0.63	-$ 342,589
6	$ 168,858	0.57	$ 96,249
7	$ 168,729	0.52	$ 87,739
8	$ 166,625	0.48	$ 79,980
9	$ 169,553	0.43	$ 72,908
10	$ 166,155	0.40	$ 66,462
		NPV[c]	$ 1,076,535

[a] In Year 5, the company assumes a battery cost replacement of US$800/household, or US$ 712,000 in total.
[b] *k* is the discount rate, which is 9.7%.
[c] The NPV is the sum of the present values of all the future cash flows (summation of the last line in the table)

[6] Estimated from the literature review (Vides-Prado et al., 2018) and semi-structured interviews with off-grid providers.