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Development of Rural Load Archetypes based on Energy Sufficiency for Improved off-grid Energy Planning in Bolivia

Tesi di Laurea Magistrale in
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Abstract

The Sustainable Development Goals (SDG 7) aim to achieve universal access to reliable, affordable, and modern energy services by 2030. However, around 770 million people worldwide still lack access to electricity, with the majority residing in rural areas of developing countries. Energy System Modelling (EMS) has been effective in developing customized off-grid solutions and integrating them into larger electrification plans for efficient and effective distribution. However, the scientific community has long focused on constructing highly detailed supply energy system models and neglected to adequately characterize demand, which represents a fundamental exogenous input for these models. This led to unreliable demand estimations and improper sizing, resulting in unsustainable energy systems over time. On this premises, the aim of this research study is to develop a methodology that can provide a preliminary estimate of the electrical demand for non-electrified rural communities to support the formulation of cost-effective electrification strategies. The methodology is applied to small rural communities in Bolivia. The initial part of the work focused on understanding the importance of an accurate electrical demand characterization, which must be linked to communities' unique energy needs and contexts, to guarantee a sustainable development. The electrical demand characterization of rural Bolivian communities started with the re-conceptualization of the energy sufficiency concept. This approach recognizes the inter-linkage between energy and all aspects of community life, including education, health, and social participation. It is tailored to the unique socio-economic factors of rural areas in developing countries and establishes a minimum level of energy services required to ensure dignified living conditions, enabling continuous economic and social development. The second part of this work focused on load estimation of un-electrified rural communities using settlement specific socio-economic factors and integrating them into energy modelling. This was done through a top-down approach, which creates load demand archetypes, designed to reproduce un-electrified rural communities, based on three main drivers: altitude, poverty level, and community size. The resulting community archetypes are valid at the national level and provide a comprehensive understanding of how different combinations of these three primary drivers impact electrical demand. The proposed archetypes also offer an approach to modelling a community's complete structure, incorporating residential, community services, and IGAs sectors. The residential sector modelling and archetype creation methodology were validated using real data on monthly electrical consumption from across Bolivia, improving the accuracy and reliability of the methodology. Lastly, by applying our top-down methodology to three case studies, we have proved its major impact in determining the optimal sizing of hybrid mini-grid systems. In conclusion, this study has established the pressing need to focus on characterizing electrical demand and its pertinence in Bolivian rural areas. Our approach has highlighted the importance of accurately assessing load demand for effectively modelling energy system solutions, which can lead to cost savings, improved energy strategies, and increased sustainability of the assessed systems.

Keywords: energy and development; access to energy; energy modelling; demand modelling; electricity demand estimation.

Abstract in lingua italiana

Raggiungere l'accesso universale a servizi energetici affidabili, convenienti e moderni entro il 2030 è uno dei 17 Obiettivi di Sviluppo Sostenibile delle Nazioni Unite. Tuttavia, circa 770 milioni di persone nel mondo sono ancora prive di accesso all'elettricità, la maggioranza delle quali risiede nelle aree rurali di paesi in via di sviluppo. Nel corso degli ultimi decenni, la modellizzazione di sistemi energetici si è dimostrata uno strumento chiave per lo sviluppo di soluzioni decentralizzate, per la loro integrazione in piani di elettrificazione più ampi e per assicurarne una distribuzione efficiente ed efficace. La comunità scientifica si è concentrata a lungo sulla costruzione di modelli di sistemi energetici altamente dettagliati, ma ha trascurato di caratterizzare adeguatamente la domanda elettrica, che rappresenta un input fondamentale per questi modelli. Di conseguenza, molti di questi sistemi si sono rivelati insostenibili nel tempo a causa di stime di domanda non affidabili che hanno provocato dimensionamenti non ottimali. Su questa premessa, lo scopo di questo studio è sviluppare una metodologia in grado di fornire una stima preliminare della domanda elettrica per le comunità rurali non elettrificate, al fine di supportare la formulazione di strategie di elettrificazione. La metodologia è applicata a piccole comunità rurali in Bolivia. La parte iniziale del lavoro si è concentrata sulla comprensione dell'importanza di una caratterizzazione accurata della domanda elettrica, che deve essere collegata alle esigenze energetiche e contesti unici delle comunità, per garantirne uno sviluppo sostenibile. La caratterizzazione della domanda elettrica delle comunità rurali boliviane è iniziata con la ridefinizione del concetto di sufficienza energetica. Questo approccio riconosce l'interconnessione tra energia e tutti gli aspetti della vita comunitaria, inclusi l'istruzione, la salute e la partecipazione sociale. Tale concetto viene costruito al fine di adattarsi a fattori socioeconomici unici delle aree rurali dei paesi in via di sviluppo, stabilendo un livello minimo di servizi energetici necessari per garantire condizioni di vita dignitose e consentendo uno sviluppo economico e sociale continuo. La seconda parte di questo lavoro si è concentrata sulla stima della domanda elettrica delle comunità rurali, non ancora elettrificate, utilizzando fattori socioeconomici specifici delle zone rurali analizzate. Ciò è stato ottenuto attraverso un approccio top-down, che crea archetipi di domanda elettrica, progettati per riprodurre le comunità rurali non elettrificate, sulla base di tre fattori principali: altitudine, livello di povertà e dimensioni della comunità. Gli archetipi di comunità che ne derivano sono validi a livello nazionale e forniscono una comprensione completa di come le diverse combinazioni di questi tre fattori influenzino la domanda elettrica. Gli archetipi proposti offrono anche un approccio per modellare la struttura completa di una comunità, incorporando i settori residenziale, dei servizi alla comunità e delle attività produttive. La modellazione del settore residenziale e la metodologia di creazione degli archetipi sono state convalidate utilizzando dati reali sul consumo elettrico mensile di tutta la Bolivia, migliorando l'accuratezza e l'affidabilità della metodologia. Infine, applicando la metodologia top-down a tre casi di studio, ne abbiamo dimostrato l'impatto nel determinare il dimensionamento ottimale di sistemi mini-grid. In conclusione, questo studio ha stabilito l'urgente necessità di concentrarsi sulla caratterizzazione della domanda elettrica e sulla sua pertinenza nelle aree rurali boliviane. Il nostro approccio ha evidenziato l'importanza di valutare accuratamente la domanda di carico per modellare efficacemente sistemi energetici decentralizzati, che possono portare a risparmi sui costi, a migliori strategie energetiche e a una maggiore sostenibilità dei sistemi valutati.

Parole chiave: energia e sviluppo; accesso all'energia; modellazione energetica; modellazione di domanda; stima della domanda di elettricità.

Contents

1 | Introduction

1.1. Background

The United Nations (UN) Agenda 2030, also known as the Sustainable Development Goals (SDGs), was adopted in 2015 by 193 countries with the goal of developing a world that is socially inclusive, economically prosperous, and environmentally sustainable for all by the year 2030. The United Nations (UN) acknowledged the crucial role that the energy sector plays in modern global challenges by dedicating SDG7 to energy. SDG 7 aims to "Ensure access to affordable, reliable, sustainable and modern energy for all", diving into the complex and multi-faceted nature of the energy challenge that requires all-inclusive approaches to address its economic, social, and environmental dimensions [7].

However nowadays, around 770 million people around the world do not have access to electricity, and an estimated 2.5 billion rely on the traditional use of solid biomass to cook their meals. The task of achieving universal access to electricity becomes increasingly difficult as a country approaches 100% electrification, as the remaining unconnected communities are often located in remote and difficult-to-reach rural areas. In fact, a significant portion of those without access to energy are situated in rural areas of developing countries, where access to resources, infrastructure, and information is often limited in comparison to urban areas in developed economies [2].

Therefore, proper different energy strategies, adapted to the complexities of specific rural contexts in developing countries, are imperative for addressing this crucial issue. This requires careful energy planning to develop customized technological solutions and integrate them into a larger national electrification program for efficient and effective distribution. Indeed, it is key to recognize that there is no one-size-fits-all solution to achieving SDG 7 and that a just energy transition must be tailored to the specific needs of each country's rural communities, recognizing the pivotal role that energy access plays in promoting economic growth and human development, as well as environmental sustainability.

In this framework, energy system modelling (EMS) plays a fundamental role as a powerful tool for energy planning and policy decision-making. In fact, it can provide valuable insights into the feasibility, cost-effectiveness, and sustainability for the best path forward rural electrification to practitioners and policymakers. Therefore, energy system modelling can help identifying the most suitable off-grid energy solutions (sizing) and the optimal deployment and integration strategies [4].

1.2. Energy planning solutions

Despite significant progress in increasing access to electricity, there is still a significant population without access, especially in rural and isolated areas of developing countries. According to the International Energy Agency (IEA) and others, the global access to electricity rate increased from 86% in 2014 to 91% in 2020, but over 700 million people still lack access to any source of electricity, with 84% of them residing in rural areas [2]. This highlights the need for continued efforts to achieve universal access to energy services.

The electrification of remote areas has been a challenge for many developing countries. While the traditional solution is to extend the national electricity grid, this approach is not always feasible due to long distances, low energy density, and high costs. In these cases, alternative solutions such as stand-alone systems and mini-grids, also known as Distributed Generation technologies, offer viable options for electrification.

The centralized electricity solutions primarily serve users in urban areas of developing countries, leaving rural populations with limited access. The costs of extending the national grid to rural areas with low population density are high, making decentralized solutions necessary to speed up electrification. To address this disparity, decentralized solutions are necessary to speed up electrification in rural areas. Off-grid solutions can be classified into three categories: stand-alone systems, which serve one consumer with one energy source; micro-grids, which serve multiple consumers but have one source; and hybrid micro-grids, which have multiple sources and serve one or more consumers. A more detailed description of the off-grid characteristics and differences, as review by [47], is shown in Table 1.1.

In conclusion, the selection of electrification technologies depends on various factors such as costs, energy density, distance, and population density. The main drivers when choosing between stand-alone systems, extension of the national grid, and mini-grids for electrification in developing countries are:

1. Cost: The cost of extending the national grid to remote and rural areas can be high, while stand-alone systems and mini grids can offer more cost-effective solutions.

2. Energy demand: The energy demand of a community will play a role in determining the most appropriate electrification technology. For example, if the energy demand is

OFF-GRID SYSTEMS MATRIX	DECENTRALIZED		DISTRIBUTED
Rural Energy Uses	Stand-alone Systems	Micro-Grid Systems	Hybrid Micro-Grid Systems
Household basic needs	Home-based Systems	Systems including a distribution grid	Systems including a distribution grid
Community services	Community-based Systems		
Productive uses	Productive-based Systems		
Consumer Number	Single	Multiple	Single OR Multiple
Energy Sources	Single		Multiple

Figure 1.1: Off-grid Systems Matrix for rural electrification systems.

low, a stand-alone system may be sufficient, while higher energy demand may require a mini-grid solution.

3. Accessibility: The accessibility of a community to the national grid, as well as the distance to the nearest grid connection, is a major factor in the selection of electrification technology.

Decentralized solutions, such as mini-grids and stand-alone systems, are becoming increasingly popular in rural areas where extending the national grid is not feasible, offering a viable alternative to traditional centralized solutions.

1.3. The pivotal role of mini-grids

Research has shown that mini-grids (including hybrid microgrids) can provide more development opportunities than stand-alone systems, as they can supply electricity for productive uses, drive economic growth, and help communities escape poverty [47],[32].

The provision of electricity through mini-grid technology has the potential to trigger a positive feedback loop that can enhance the economic development of communities. The positive feedback loop refers to a self-reinforcing relationship between electricity access through mini-grid technology and the development of communities. This relationship starts with the provision of electricity, which creates new economic activities that depend on it (called "Productive Uses of Energy") and improves the performance of existing income-generating activities (IGAs). These productive uses increase the demand for electricity and result in income growth, leading to a rise in total electricity demand and revenue for the energy system manager. This cycle of improved access to electricity and increased economic growth continues to reinforce each other, leading to overall development of the community [62].

However, empirical studies have shown that this relationship between electricity access and community development is not a guaranteed outcome and is highly dependent on many socio-economic, infrastructural, and cultural factors [8],[60],[62]. The effectiveness of this positive feedback loop is highly context-specific and depends on the presence of preconditions that support it. This highlights the importance of a comprehensive and nuanced approach to electrification projects that considers the unique needs and context of each community.

A recent report by the International Renewable Energy Agency (IRENA) confirms the growth of decentralized renewable-based solutions for electrification, particularly in the mini-grid sector. Between 2010 and 2019, the number of people connected to mini-grids using solar, hydro, and biogas technologies has more than doubled, reaching 11 million in 2019 [3].

1.4. Open challenges

Although the important role of mini grids in achieving SDG 7 has been acknowledged, their full potential has yet to be realized. One of the significant barriers to the sustainability of these systems is the complex and critical process of sizing. Incorrect sizing can result in poor service quality, customer dissatisfaction, technology abandonment, and high tariffs that are not attractive to investors, hindering the sustainability of the systems. Effective sizing is therefore crucial in ensuring the success and sustainability of mini grid systems [11].

Additionally, the deployment of mini grids must consider geographical, time, and financial constraints, making the implementation of optimal electrification strategies a crucial challenge. In fact, an effective deployment strategy can greatly speed up the process and ensure the success and sustainability of mini grid systems. Therefore, proper planning and selection of technologies, along with a thorough understanding of the local context, are essential in achieving the full potential of mini grids and achieving SDG 7.

To overcome the challenges in the implementation of mini grid systems, it is essential to start by evaluating the optimal off-grid solution that will effectively meet the energy demand of rural communities while considering the appropriate size of the system. As a supporting tool in this evaluation process, the energy system modelling approach is often used. The energy demand is one of the main exogenous input parameters needed by these kind of models together with the assessment of the renewable energy potential of the zone under study.

Therefore, It is essential to understand the role of energy demand in energy system modelling. The quality of the energy demand data used as an input is crucial for the accuracy of the energy system modelling results. If the energy demand is poorly assessed and characterized using low-quality data, the results of the model will be affected. This means that no matter how technologically advanced and precisely resolved the energy model is in terms of geographical and temporal aspects, if the input data is poor, the output will be unreliable. The saying "garbage in, garbage out" is relevant in this case, as the model is only a tool that relies on the quality of the input data. Hence, it is essential to provide accurate and high-quality energy demand data to ensure the reliability of the modelling results.

1.5. Aim of the research: General and Specific objectives

1.5.1. General objective

The general objective of this work is to contribute to the field of energy modelling for the purpose of enhancing electrification strategy formulation and off-grid energy system sizing. This will be achieved by focusing specifically on improving the characterization of energy demand, which plays a critical role as an input in energy modelling.

1.5.2. Specific objective: Characterization of the demand

The purpose of this study is to address gaps in energy planning for developing countries, as identified in the literature. The scientific community has long focused on constructing highly detailed supply energy system models but has neglected to adequately characterize demand. As a result, many of these systems have proven unsustainable over time due to unreliable demand estimations that caused over-sizing [11].

In this context, the specific objective of this thesis is to characterize demand based on the basic energy needs of targeted communities. Recognizing the unique needs and context of each community is crucial to develop a conceptualization and methodology that can accurately describe how meeting their electrical load can drive continuous social and economic development and improve quality of life. This requires a demand modelling approach that is flexible and considers how different parameters such as the poverty status, geographical location, and size of the targeted community, affect the needs and structure of a community.

Additionally, the current energy models inadequately account for cross-sectoral and cross-disciplinary interactions. This study aims to address this issue by developing a methodology that emphasizes how energy is closely linked to all sectors of the community, including education, governance, social participation and others. In particular a special focus is given to the relevance of agricultural and transformation activities that are often neglected when it comes to energy access projects.

1.5.3. Specific objective: Rural energy demand estimation

It is worth noting that while models, particularly bottom-up approaches, for characterizing the demand in rural areas already exist, they often require high resolution detailed input data regarding the types of appliances owned and the patterns of usage in the target area [45],[48]. This represents a significant problem since, especially in developing countries, the availability and reliability of these kind of information is often limited or even missing. In fact, data paucity represents one of the main challenges for energy modelling in developing countries [29]. Moreover, pre-electrification studies aim at predicting the evolution of demand over time trying to forecast future appliances usage of people that never experienced electricity before by collecting information through surveys. Indeed, the results coming from those evaluations proved to be incorrect [17].

Therefore, the significance of accurately determining the demand has been acknowledged and the critical elements to consider have been emphasized. The effort then moves forward to put into practice a methodology to forecast the electrical demand of non-electrified communities starting by thoroughly understanding their needs.

The proposed methodology focuses on the development of a practical and straightforward tool, through the construction of multiple archetypes, that allows to perform a preliminary energy demand estimation tailored to the specific needs and context of targeted communities. The archetypes have been designed to reproduce the entire Bolivian rural communities by making precise distinctions based on climate zones, poverty indicators, and household's number. This translates into a top-down approach based on three macro parameters coupled with a bottom-up energy demand model (RAMP) that allows a first round demand assessment of energy sectors in rural communities without the support of high data intensity.

This methodology could support the identification of the most suitable locations, where more detailed and thorough assessments can start, improving the accuracy and efficiency of electrification planning. In fact, its low computational and financial requirements, along with its ease of use, and possible integration with Geospatial Electrification Modelling through Geospatial Information Systems, could support the formulation of cost-effective electrification strategies to meet different energy demands in rural areas.

Furthermore, the proposed approach is meant to be flexible and adaptable, with the ability to adjust to changes in energy resources, demands, and local constraints, making it reusable in other contexts and countries.

1.6. Road map of the thesis

1. **Measuring energy access.** In this chapter the relevance of properly characterizing the demand and linking it with development needs of populations has been assessed, culminating in the re-conceptualization of the energy sufficiency status. Different quantitative and qualitative approaches for the measurement of energy access are explored through a literature review that highlights the most important ones for the field under study.

2. **The Bolivian case study**. Context about the Bolivian case study is given.

3. **Methodology**. This chapter contains the methodology followed in the various phases of the work.

4. **Results and Discussion**. The methodology's results are discussed.

5. **Conclusions**. The final main conclusions of the work are given.

2 | Measuring Energy Access

2.1. The importance of measuring energy access

Access to modern energy services is fundamental to economic, social, human, and sustainable development. In fact, reliable and affordable energy is needed to: improve living standards, gender and social inequality, support health and educational services, assist enterprises and communities' facilities [41][62]. As a consequence, access to energy is not considered as a final and separate goal by itself but instead it plays an instrumental role that allows to pursuit other ends[16]. Indeed, [7].

Traditionally energy access has been measured in a binary way, describing, for example, a condition in which a household electricity connection can be either present or not. Even if this approach is simple and relies on solid data it has its own disadvantages. In fact, it can be representative of a distorted picture failing in the characterization of those multiple attributes cited in the SDG 7. This method is unable to determine if energy services are provided in sufficient quantity and quality, thus preventing further assessments on reliability or affordability of the access status. As a matter of fact, binary metrics cannot explain the phenomenon of expanding energy access and how it impacts socioeconomic development either. Furthermore, energy for cooking and heating needs, as well as for productive engagements and community facilities are not considered in the assessment, representing another significant limitation. In addition, the traditional approach failed in the accounting of technologies evolution over time: solutions such as solar lighting kits are not contemplate as systems that can allow an energy access [16].

Recently, the challenge of defining the energy access has been extended to the world of social sciences encompassing major and complex issues such as equity, justice and sufficiency [20]. These new concepts must be declined and analysed in the distribution and management of energy systems and services respecting environmental limits.

For all these reasons, over the years, several attempts have been made to craft new frameworks and definitions for measuring access to energy using innovative approaches and methodologies. The goal of the next sections is to describe and analyse the most important ones focusing on the context under study that involves electricity access. In fact, electricity access has a more limited scope focused on electricity provision and services while energy access is a more comprehensive and holistic concept that takes into account multiple aspects of energy delivery. First, a practical and quantitative framework for the measurement of energy access is analysed, then two new and complex energy related topics, still at an initial stage of conceptual development, are discussed.

2.2. Quantitative frameworks to measure energy access

There are several quantitative frameworks that have been developed to measure energy access. Among the most important approaches, designed by well-known international agencies, there are:

1. The Global Tracking Framework (GTF), developed by the International Renewable Energy Agency (IRENA).
2. The Energy Access Outlook framework, developed by the International Energy Agency (IEA).
3. The Multi-Tier Framework (MTF) , developed by the Sustainable Energy for All (SEforALL) initiative.

All these frameworks are used as a powerful tool to measure the progress towards the achievement SDG 7, identifying areas where more action is needed. Among these threes, the MTF is widely accepted by the international community due to the nature of the SeforALL initiative which is a global partnership including governments, international organizations, civil society, and the private sector. For example both the World Bank and the United Nations Development Programme have used this methodology [31]. In addition, MTF is a flexible framework characterized by high adaptability to specific needs and contexts of different countries and regions. All of these reasons make a deeper analysis of the framework worthwhile.

2.2.1. Multi-Tier Framework

This framework aims at a new definition and measurement of energy access taking into account quantity and quality of the electricity provided as well as extending its area of interest to households, productive engagements, and community facilities.The multi-tier framework is utilized to evaluate performance, establish goals, prioritize investments, and monitor progress. Some key concepts and terminology, used in MTF, must be examined and understood:

1. Access to energy is not a straightforward concept. The distinction between access to energy supply, access to energy services and usability of supply must be clear. Thus the following definitions are provided as written in [16]:

   (a) **Access to energy services**: The ability of an end user to utilize energy services (such as lighting, phone charging, cooking, air circulation, refrigeration, air conditioning, heating, communication, entertainment, computation, motive power, etc.) that require energy appliances and suitable energy supply.

   (b) **Access to energy supply**: The ability of an end user to utilize an energy supply that can be used for desired energy services.

   (c) **Usability of energy supply**: The potential to use energy supply when required for desired energy services. Usability can be enhanced by improving the attributes of energy supply, such as capacity, availability, reliability, affordability, safety, convenience, etc.

2. Sustainable development conjugated in all its dimensions (economic, social, human) is the main focal point of expanding energy access.

3. In order to obtain a comprehensive development process, the use of energy services must be considered across households, productive engagements, and community facilities.

4. Only electricity access related features are discussed due to rural electrification focus of the work thesis.

Key features

The fundamental and innovative features of the MTF can be summarised as follows:

1. **Focusing on the user's point of view of energy services**. The MTF is not only assessing if an energy service is being delivered but it is also focused on the user's perspective looking if this service is actually "usable".

   Therefore, the MTF has identified key attributes that together affect the usability of energy for desired services. The attributes include capacity, availability, reliability, affordability, quality, legality, health impact, safety, and convenience. Thus, the MTF encompasses all the attributes mentioned in the SDG 7 definition. For example, the framework considers:

      i. The quantity of the electricity that is delivered.

ii. For how long the user can benefit of the electricity service every day.

iii. If the service is reliable and of good quality (e.g. outages and voltage fluctuations), affordable, legal and safe.

2. **Tiers as classification of energy service levels**. The MTF describes energy access as a continuum of service levels that are allocated into tiers. Thus, improvements in energy access are conceived as a progression of increasing levels of energy attributes. The classification starts from absence of service (Tier 0) to full service (Tier 5) as showed in Figure 2.1. Concerning electricity, Tier 1 represents a starting basic level where lighting and cell phone charging are provided. Accessing to higher tiers allows improvements in capacity and service duration as well as the ability of purchasing more domestic appliances. This new structure of energy service levels overcome the traditional binary conceptualization that represented one of the previous highlighted limits to deal with.

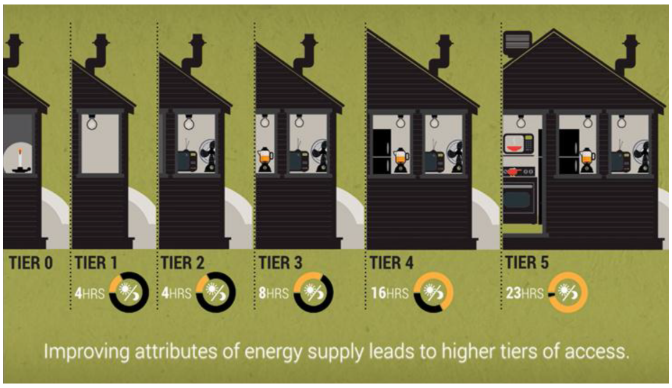


Figure 2.1: Access as a continuum of energy services.

3. **Technology-neutral**. The MTF allows aggregation of different technologies with different service levels. Therefore the approach is independent from how the service is provided because the real focus is placed on whether the standards for each tier are met. For example, a grid connection can be rated higher or lower than a solar home system depending on how energy access is delivered in the two systems.

Overall structure

The structure used in the MTF encompasses different areas of energy use (households, productive engagements, and community facilities) also called "locales" of energy access. Each of those areas can be further break down into different sub areas called sub locales. For example, for the households the overall structure comprehends: (i) access to electricity, (ii) access to energy for cooking solutions, and (iii) access to energy for space-heating solutions.

Each sub locale can be considered separately giving different perspectives of the same picture. In general, the following concepts are applied through each of the three main areas of interest (locales):

1. The lowest tier ranking determines the overall access level for each framework. For example, if all the attributes of a general framework satisfy tier 4 but there is one attribute reaching only tier 3, then the overall level is determined by the tier 3.
2. Separate multi-tier frameworks are defined for each of the sub locales as well as separate indices of energy access with a tier rating adjusted to a scale of 100.
3. The overall index of a main area of access to energy is calculated as the average of the sub-locale indices.
4. An overarching index of access to energy can be calculated as the average of the indices across the three locales: households, productive uses, and community facilities.
5. The overall index across the three locales as well as the average indices across sub-locales, involves an apples-to-oranges aggregation that is less relevant than the individual indices.

The following figure 2.2 shows the overall structure of the framework. .

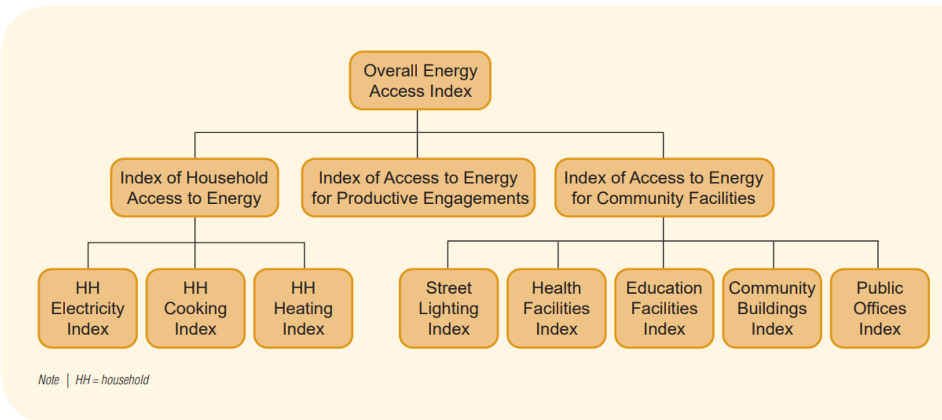


Figure 2.2: Hierarchy of energy access indices.

Concerning energy access for households, it has been decided to limit the analysis only on access to electricity since describing access for cooking solutions and for space-heating is not the focus of the research study.

Household Access to Electricity

The household access to electricity encompasses several perspectives and separate multi-tier frameworks listed below :

1. Electricity supply multi-tier framework, summarized in Figure 2.3.
2. Electricity services multi-tier framework based on the type of appliances used, is summarized in Figure 2.4.
3. Electricity consumption multi-tier framework, summarized in Figure 2.5.

In all the three frameworks listed above is possible to notice their interconnection and the fundamental features of this new methodology, conjugated in the different areas of supply, services and consumption. In fact, a progressive improvement in electricity supply can trigger growth and improved access to electricity services thus impacting positively on the consumption too. Therefore, the MTF for electricity services is strictly related with the tiers of electricity consumption. However,tiers of consumption are distinct from tiers of energy services, which are different from tiers of energy supply as well.

In conclusion,it is possible to obtain different tier ratings across the three multi-framework described. For example differences in access ratings between supply and services could be explain with: good availability of appliances despite poor supply or inability to afford appliances despite adequate supply.

Access to energy for productive engagements

Productive uses of energy are defined as activities that are responsible for an increase in income or productivity. Unfortunately the complex and multiple categories in which productive activities are involved hampers the design of a common metric to measure energy access. In fact, productive activities can involve several energy applications that could imply different energy sources. The categories in which energy applications can be classified are: information and communication, motive power, space heating, product heating, and water heating.

The process involved in the measurement of the energy access is the following:

i. Identification of earning members at household level and their productive engagements.

ii. Identification of relevant and critical energy applications that can influence productivity.

ATTRIBUTES		TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
1. Peak Capacity	Power capacity ratings[28] (in W or daily Wh)		Min 3 W	Min 50 W	Min 200 W	Min 800 W	Min 2 kW
			Min 12 Wh	Min 200 Wh	Min 1.0 kWh	Min 3.4 kWh	Min 8.2 kWh
	OR Services		Lighting of 1,000 lmhr/day	Electrical lighting, air circulation, television, and phone charging are possible			
2. Availability (Duration)	Hours per day		Min 4 hrs	Min 4 hrs	Min 8 hrs	Min 16 hrs	Min 23 hrs
	Hours per evening		Min 1 hr	Min 2 hrs	Min 3 hrs	Min 4 hrs	Min 4 hrs
3. Reliability						Max 14 disruptions per week	Max 3 disruptions per week of total duration <2 hrs
4. Quality						Voltage problems do not affect the use of desired appliances	
5. Afford-ability					Cost of a standard consumption package of 365 kWh/year < 5% of household income		
6. Legality						Bill is paid to the utility, pre-paid card seller, or authorized representative	
7. Health & Safety						Absence of past accidents and perception of high risk in the future	

Figure 2.3: Multi-tier Matrix for measuring access for household electricity supply.

	TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
Tier criteria		Task lighting AND Phone charging	General lighting AND Phone Charging AND Television AND Fan (if needed)	Tier 2 AND Any medium-power appliances	Tier 3 AND Any high-power appliances	Tier 2 AND Any very high-power appliances

Figure 2.4: Multi-tier Matrix for measuring access for household electricity services.

	TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
Annual consumption levels, in kWhs		≥4.5	≥73	≥365	≥1,250	≥3,000
Daily consumption levels, in Whs		≥12	≥200	≥1,000	≥3,425	≥8,219

Figure 2.5: Multi-tier Matrix for measuring access for household electricity consumption.

iii. Identification of the most important energy source for each application.

iv. Evaluation of the energy supply through the key attributes.

v. Energy access is assessed for each application separately.

vi. The lowest tier among all applications determines the energy access rating for the productive use as a whole.

In the Figures 2.6 and 2.7 it is possible to appreciate the multi framework that has just been described.

ATTRIBUTES			TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
1. Capacity	Electricity	Power		Min 3 W	Min 50 W	Min 200 W	Min 800 W	Min 2 kW
		Daily Supply Capacity		Min 12 Wh	Min 200 Wh	Min 1.0 kWh	Min 3.4 kWh	Min 8.2 kWh
		Typical Technology		Solar lanterns	Standalone solar systems	Generator or mini-grid	Generator or grid	Grid
	Nonelectric (fuels, RME, RTE, AP, HP)					Available nonelectric energy partially meets requirements	Available nonelectric energy largely meets requirements	Available nonelectric energy fully meets requirements
	Both					No relevant application is missing solely due to capacity constraints		
2. Availability (Duration) of Daily Supply	Electricity			Min 2 hrs	Min 4 hrs	Half of the working hours (min 50%)	Most of working hours (min 75%)	Almost all working hours (min 95%)
	Nonelectric (fuels, RME, RTE, AP, HP)					Available nonelectric energy partially meets requirements	Available nonelectric energy largely meets requirements	Available nonelectric energy fully meets requirements
	Both					Longer working hours are not prevented solely by lack of adequate availability (duration) of supply		
3. Reliability							Reliability issues with moderate impact	No reliability issues or little (or no) impact
4. Quality							Quality issues with moderate impact	No quality issues or little (or no) impact
5. Affordability							Variable energy cost ≤ 2 times the grid tariff	Variable energy cost ≤ the grid tariff

Figure 2.6: Multi-tier Matrix for Measuring Access to Productive Applications of Energy .

Access to energy for community facilities

For community facilities, five sub-locales are considered: (i) health facilities, (ii) educational facilities, (iii) street lighting, (iv) government buildings, and (v) public buildings. Energy for community facilities can drive important socioeconomic changes. For example, it can impact how education and health services are delivered, increasing their quality and the number of people using them. Or it can improve security and social activities through a better street lighting service.

ATTRIBUTES		TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
6. Legality						Energy bill is paid to the utility, pre-paid card seller, authorized representative, or legal market operator	
7. Convenience						Convenience issues cause moderate impact	Little (or no) convenience issues or little (or no) impact
8. Health (IAQ from use of fuels)	PM2.5 (μg/m^3)		[To be specified by competent agency such as WHO]	[To be specified by competent agency such as WHO]	[To be specified by competent agency such as WHO]	< 35 (WHO IT-1)	< 10 (WHO guideline)
	CO (mg/m^3)					< 7 (WHO guideline)	
	OR Use of fuels (BLEENS)			Use of non-BLEENS solutions (if any) outdoors or with smoke extraction		Use of BLEENS or equivalent solutions only (if any)	
9. Safety						Energy solutions caused accidents that did not require professional medical assistance	Energy solutions did not cause any accidents

Figure 2.7: Continuation of MTF for Productive Applications of Energy.

Community facilities have a wide variety of categories involving different scopes and energy uses. For this reason designing a common metric for the measurement of energy access is challenging. For example street lighting has to consider attributes such as coverage and brightness, whereas the framework for community institutions encompass a broader variety of energy services and sources. In the following Figure 2.8 is possible to observe the street lighting framework while the community institution ones mirrors almost exactly the already mentioned framework for productive uses of energy 2.6. Therefore it is possible to appreciate better their difference of approach making a comparison between the twos.

STREET LIGHTING	TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
ATTRIBUTES: 1. Capacity		At least one functional street lamp in the neighborhood	At least 25% of the neighborhood is covered by functional street lamps	At least 50% of the neighborhood is covered by functional street lamps	At least 75% of the neighborhood is covered by functional street lamps	At least 95% of the neighborhood is covered by functional street lamps
2. Availability (duration)		Street lighting functions for at least 2 night hours each day	Street lighting functions for at least 4 night hours each day	Street lighting functions for at least 50% of night hours each day	Street lighting functions for at least 75% of night hours each day	Street lighting functions for at least 95% of night hours each day
3. Reliability					No reliability issues perceived by users	
4. Quality					No brightness issues perceived by users	
5. Safety					No perceived risk of electrocution due to poor installation or maintenance	

Figure 2.8: Multi-tier Matrix for Access to Street Lighting.

2.3. Energy justice

For years in Europe, energy standards and policies have been focused on system performance and efficiency. These specific improvements often focused on technological and technical innovations neglecting the possibility of a human-centred and social science exploration of energy developments. Therefore, not considering the real-world human impact has produced deep consequences. Countries have experienced the benefits of improved systems while others in return have suffered negative externalities such as poor health conditions or inadequate energy access. Being completely excluded from those advantages has raised concerns about justice and equity that are unfamiliar and challenging topics to merge into the energy field research [66].

Therefore, the energy justice concept has been introduced into the literature [40] [49]. It is aimed at fostering equity meaning that it should involve mechanisms designed to offer individuals and communities equal access to energy opportunities. Justice is seen as the tool through which equity can be reached. Equity includes the existence of specific groups of people that may need different solutions to facilitate a fair and equal access. For example, a rural indigenous community, located in a developing country, may need a different energy access solution in comparison with some other cases [66].

Energy justice is a recently new concept that still needs further research being at an initial phase of conceptualization. It involves the challenge of applying justice principles to energy in all its forms such as energy policy, energy consumption and production fields. Energy justice aims at the identification of where an injustice has emerged, who is affected by it and how is possible to resolve or reduce such injustice [40]. The analysis of this procedure is described in the three tenets that are the foundation of the energy justice concept: distributional justice, recognition-based justice and procedural justice.

2.3.1. Distributional justice

Distributional justice seeks where the energy injustices occur. It aims at the identification of both the physically unequal allocation of energy benefits and ills and the uneven distribution of their associated responsibilities. For example, studies related to the energy prices concerning the consumption view of final users have shown how already poor and isolated communities pay a relatively higher share of their total income for lower quality energy sources in comparison with higher income and more urbanised societies [40]. This phenomenon testifies the uneven distribution of financial burdens related to affordable access to energy services. Distributional justice concerns not only access to energy services, but the siting of infrastructure too. Thus, distributional justice focuses on a fair distribution of advantages and disadvantages among all members of society regardless of income, gender, culture, race, etc.

2.3.2. Recognition-based justice

Recognition-based justice seeks at the identification of sections of society that are ignored or misrepresented. It recognizes that each individual or group of people must be equally represented, free from physical threats and with complete political rights. The failure to recognise or even misrecognise could happen for several reasons such as cultural or political domination. This causes the inability to acknowledge potential useful information from marginalized social groups, creating injustice. Thus, recognition-based justice focuses on the detection and acceptance of divergent perspectives rooted in social, cultural, ethnic, racial and gender differences [40].

2.3.3. Procedural justice

Procedural justice explores how people are engaged and considered in energy decision-making processes that usually regulate the distribution of benefits and burdens described above [66]. Therefore, it seeks fair practices to pursuit commitment of all stakeholders in a non-discriminatory way. Developing a sense of acceptance and ownership among communities is key and it can be achieved through several mechanisms of inclusion: local knowledge mobilization, clear disclosure of information and improved institutional representation [40].

2.3.4. Describing a just world

In conclusion, it is possible to summarize the main characteristics associated to the concept of energy justice as:

1. Equitable distribution of both benefits and burdens involved in the production and consumption of energy services. Therefore, consideration of environmental and social impacts, always energy related, across space and time.
2. Recognition of equitable energy access regardless of social, racial, gender, income etc differences. This considers acknowledging excluded social minorities and differences between developed and less developed countries.
3. Fair treatment of people and communities in energy decision making, ensuring basic civil rights and full representation through inclusion mechanisms.

2.4. Energy sufficiency

Around 2003, the process of designing a totally new policy paradigm of sufficiency in energy services started in Europe [20]. Initially the topic of energy sufficiency was not clearly defined but it was connected to reducing energy consumption while recognising and respecting environmental limits. It is worth noting that the word "sufficiency" can have both a positive and a negative meaning as something related to excess or to the just right amount of something that is enough. However, at the beginning of the debate in Europe, the term was mostly related to reducing consumption. But, as time as passed, the energy sufficiency concept has developed around more complex issues and thus it is fundamental to have a deeper comprehensive perspective of them all. A simple and initial definition has been given by [20]:

"*Energy sufficiency is a state in which people's basic needs for energy services are met equitably and ecological limits are respected*"

2.4.1. Energy Services and Basic Needs

Starting from the definition given, it is first mentioned the role of energy services in satisfying basic needs that encompass shelter, health, work, mobility, and communication. Energy services are those who can allow cooking, lighting, cooling, IT-based communication, automotive transport and industrial processes. To better visualise how the sufficient energy services can comply with equity and environmental limits the concept of the "Sustainable Development Doughnut" has been adapted to the energy sufficiency field as shown in the Figure 2.9.

The doughnut offers an effective representation of two principal characteristics related to energy sufficiency: the idea of sufficiency as constrained by environmental limits and at the same time the idea of sufficiency as minimum requirement to satisfy basic needs [20]. Exactly in between these two areas, it is possible to achieve energy sufficiency. However, energy services and basic needs are not straightforward concepts. They both strictly depend on the context (culturally variable) and thus they can vary according to local conditions, showing crucial difficulties for the identification of minimum standards.

For this reason, one important question is raised: how minimum requirements of energy services to satisfy basic needs can be identified ? In order to answer this question is worth mentioning the case of the Minimum Income Standard that have been designed in the UK. "This Minimum Income Standard (MIS) is calculated by specifying baskets of goods and services required by different types of households to meet fundamental needs and to participate in society". Thus, the minimum is defined as more than just food clothes and shelter

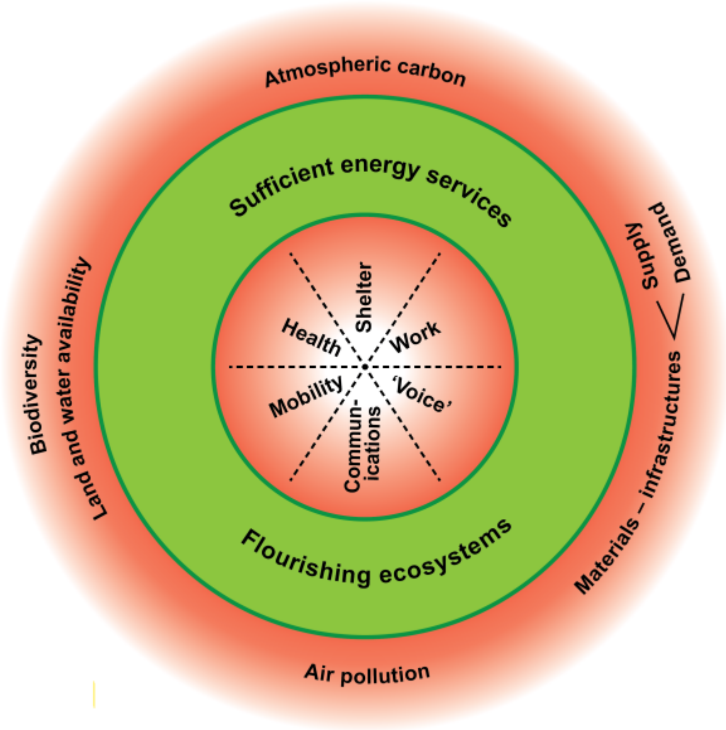


Figure 2.9: Adaptation of the Sustainable Development Doughnut model to the energy sufficiency concept.

because it also comprehends what is needed in order to have the possibility to play a part in society. Therefore, MIS covers not only necessities related to survival but also necessities heavily linked with social opportunities that are seen as a function of well-being [58].

The MIS shows a feasible method to identify minimum needs in a specified time and place through careful participatory research and social consensus and that these needs are not going to change, at least in the medium term future. This offers the potential of operationalising the concept of energy sufficiency using as a guideline the methodology followed in the MIS. Furthermore, in areas where absolute needs have been agreed on and thus implemented into policies, typically standards have been set by expert such as national or international recognized organizations or even governments.

2.5. Re-framing energy sufficiency

One of the main focus of the research is mostly developed around the design of a methodology that could define the process through which a developing country may reach the energy sufficiency status. The context under study is restricted to the electrification of rural communities further delimiting the specific area in which energy services must satisfy basic needs. Therefore, it is fundamental to overcome the risk of focusing only on sufficiency in terms of demand and consumption reduction measures that are the ones mainly devised in Europe together with energy efficiency mechanisms.

Therefore, the conceptual re-framing of the energy sufficiency, used from now on, is centred around the following guidelines:

1. Rethinking energy sufficiency lines through the lens of communities that do not yet have access to energy services represents the crucial challenge to deal with. In addition, the mismatch between developing and developed countries as well as between urban and rural zones has to be fully considered whenever talking about environmental limits, or energy justice. Thus, sufficiency must be understood in terms of social well-being and equity too.

2. As a first step to ensure electricity coverage in developing countries' rural communities, a minimum access to energy services must be defined. The intrinsic difficulties inherent to the achievement of this complex objective have already been mentioned: basic needs (that comprehend shelter, food security, health facilities, social networks, income generating activities) are normative and vary significantly depending on the climate, social customs, norms and other factors inherent to geographical location. Therefore considering how these aspects can influence the electrical demand is going to be fundamental.

3. Ideally, the achievement of the energy sufficiency status has been rethought as a position where electric consumption and supply among the community is enough to enhance a continuous economic and social development without putting at risk environment goals. In this way, the new approach tries to cover the structural evolution of a community and its development path towards energy sufficiency starting from a position of poor energy access.

4. Considering the importance of the energy mobility concept defined as: "The ability of households to increase their energy demand due to an increase in the number of electrical appliances they own or extension in usage of already owned electrical appliances". Therefore, combining energy sufficiency with the guarantee of energy mobility availability is fundamental to foster continuous development.

5. Paying attention to the important lessons learnt from the MTF and the energy justice concept that are still considered within practical limits.

The methodology describes in detail electrical features and characteristics of energy community sectors taking into consideration their regional variability and their evolution through different stages of development. Particular attention is paid in the analysis of income generating activities being aware that policy makers usually neglect those activities in the design of energy standards. This process is described in detail in Chapter 4 where it has been implemented and improved through the course of the work going from an initial phase until its final configuration.

3 | The Bolivian Case Study

3.1. Country Overview

Bolivia is a west-central South American country with a population of 11,471,000 inhabitants (2019 est.) and a total area of 1,098,581 sq. km. It occupies a landlocked territory that boarders with five different countries, characterized by a unique geography with contrasting climatic zones. The constitutional capital is the historical city of Sucre, but the administrative capital is La Paz, where the executive and legislative branches of government are located. Bolivia is traditionally considered as a highland country even if only one-third of its territory lies in the Andes Mountains. For centuries this part of the nation has been the centre of the mining, commercial, and business investment sectors, where the major important cities have developed. However, during the 20th century, the demographic and economic landscape began to change. In fact, in the eastern lowlands, the rapid and continuous development of Santa Cruz department has been playing a fundamental role for the economic growth of the country [18].

3.2. Economic Overview

Bolivia is a resource rich country with strong growth attributed to captive markets for natural gas exports to Brazil and Argentina. The mining industry, especially the extraction of natural gas and zinc, currently dominates Bolivia's export economy. However, the country remains one of the least developed countries in Latin America because of state-oriented policies that deter investment [12].

Bolivia is a middle-income country as stated by the World Bank classification. The Gross Domestic Product (GDP) in Bolivia was worth 40.41 billion US dollars in 2021 making the country the 93rd economy in the world in terms of GDP while the 134rt economy in terms of GDP per capita with a value of 4,031 US dollar [15]. With a Human Development Index (HDI) of 0.703, it is ranked 114th.

The Bolivian economy has had a historic pattern of a single-commodity focus. From silver to coca, Bolivia has enjoyed only occasional periods of economic diversification. Political instability and difficult topography have constrained efforts to modernize the agricultural sector. A lack of foreign investment in the key sectors of mining and hydrocarbons, along with conflict among social groups, pose challenges for the Bolivian economy. Rampant inflation and corruption previously created development challenges, but in the early twenty-first century the fundamentals of its economy showed unexpected improvement. In fact, between 2006 and 2019 (term of the presidency of the democratic socialist Evo Morales), GDP per capita doubled and the extreme poverty rate declined from 38% to 18% [13]. The poverty rate declined from 22.23% in 2000 to 12.38% in 2010. Moreover, the Gini coefficient declined from 0.60 to 0.446 [13].

3.3. Government administration

The country is divided into nine departments (departamentos), each of which is headed by a prefect appointed by the president. Departments are subdivided into provincias administered by subprefects. At the same time, Bolivia can also be divided into municipalities (municipios) which manage 20 percent of the public sector budget[18]. The administrative division of the Bolivian territory used in this work thesis is the following: departments, municipalities, and communities. Therefore, each department is constituted by a specific number of municipalities and each municipality, in turn, is constituted by a specific number of communities. This piece of information is fundamental to better understand future analysis and reasonings.

3.4. Zones differentiation

In order to cope with different geographical areas and climates, Bolivia may be divided into three major regions: the highlands, the valleys, and the lowlands [74]. These major regions are distinguished by three fundamental characteristics: climate, physiography and human presence. Each of these characteristics has repercussions on the others and on the life that is present in the area. For these reasons, climate and physiography are going to be further analyzed in the following sections 3.5 and 3.6.

3.4.1. Highlands

The southwestern highlands, or Altiplano, is the area where Lake Titicaca is located. Bolivia's mountainous western region is one of the highest inhabited areas of the world. In this area, the Andes are divided along the border into the Cordillera Occidental to the west and into the Cordillera Oriental to the east, that encompasses the city of La Paz.

The Cordillera Occidental is a chain of dormant volcanoes and solfataras, volcanic vents emitting sulphurous gases. The average elevation range, in most of the northern part, is around 4,000 m while the southern is lower. Rainfall is usually scarce everywhere but in the northern half is greater and characterized by land covered with scrub vegetation. On the other hand, the southern area is characterized with almost no precipitation and a landscape of largely barren rocks. Therefore, the south region of the Cordillera Occidental is mostly uninhabited, and the other regions are sporadically populated.

The Altiplano's eastern side is a continuous flat area. The entire Altiplano was originally a deep rift between the cordilleras that gradually filled with highly porous sedimentary debris coming from the erosion of the peaks. Going towards the south of the Altiplano rainfall diminishes and therefore the landscape changes from scrub sparse vegetation to barren rocks of dry clay.

The older Cordillera Oriental enters Bolivia on the north side of Lake Titicaca where the northern part, also called the Cordillera Real, encompasses a series of granite mountains peaks that often surpass 6,000 m. Going south the Cordillera changes into the Cordillera Central with elevations around 4,200 m.

3.4.2. Valleys

The north-eastern flank of the Cordillera Real is known as the Yungas, meaning "warm valley". This region, located in the northeast of La Paz, is characterized by remote hills and peaks portraying a semitropical valley. Intense rainfall, lush vegetation and narrow rivers makes the land among the most fertile in Bolivia. However, the lack of a good transport infrastructure has hindered its agricultural development. This region ranges from 2,000 to 3,000 metres above sea level, characterized by milder temperatures than those of the Altiplano. The cities of Sucre, Cochabamba, and the upper area of Tarija department, are located in this vast territory.

3.4.3. Lowlands

The eastern lowlands include all of Bolivia north and east of the Andes comprising over two-thirds of the national territory. Differences in landscape and climate, distinguish the lowlands into three areas.

The first one is the flat northern area that comprises Beni and Pando Departments together with the northern part of the Cochabamba Department. This region is characterized by tropical rain forest where heavy rainfall periodically transforms the vast part of the land into a swamp due to its poor drainage caused by clay topsoil.

Secondly, the central area, made up of the northern half of Santa Cruz Department, is characterized by small hills with gentle slopes and a drier climate than the north. In this region, forests alternate with savanna together with cultivated land. Santa Cruz, the fastest growing economy, is placed in this territory. Furthermore, most of Bolivia's petroleum and natural gas reserves are located here.

Finally, the south-eastern part of the lowlands is part of the Gran Chaco. During the rainy season, that lasts for three months, the territory is practically flooded while for the remaining part of the year precipitation is absent. This intense rainfall variation maintains only scrub vegetation and cattle grazing. However, recently natural gas and petroleum reserves have been discovered near the foothills of the Andes attracting some settlers to the region.

3.5. Climate

Climate is the determining factor that directly affects the vegetation and distribution of different ecosystems, which can implicitly provide information about their productive potential. The climatic elements considered for this purpose are temperature and precipitation. By latitude, Bolivia should have mostly a tropical climate as it occurs in the east of the country. However, if considering the altitude range, this produces great climatic variations. Therefore, it is possible to have temperate-warm to warm climate in the Chaco and tropical plains, a temperate and dry climate in the valleys and cold weather in the Altiplano [74].

3.5.1. Temperature

Ambient temperature is very important for the regulation of the vital processes of all living organisms especially in plants, which is influenced by latitude and altitude. The distribution of average temperatures is determined by altitude, which varies annually from about 25 °C in the tropics and Chaco (average temperatures between 20-26 °C), to 18 °C in the valleys (10-20 °C) and 10 °C in the Altiplano (average annual temperatures between 5-10 °C) [74].

3.5.2. Precipitation

Rainfall is important for agricultural production, since plant species of productive interest, mostly depend on the moisture contributed by rainfall. Annual accumulated precipitation ranges from about 2,000 mm in the Benian plain (tropics), from 1,300 to 1,700 mm in the Yungas (tropics), from 300 to 800 mm in the Altiplano and high valleys and from 400 to 1,200 mm in the Chaco. In Bolivia the largest distribution of rainfall occurs in the summer season (December - March), which represents between 60 - 80% of total precipitation. On the other hand, during the dry period (winter and part of autumn and spring), rainfall ranges from 0 to 20% [74].

3.6. Physiography: the importance of altitude

The various topographical formations play an important role in the economic and social activities of the country, since they influence the climatic characteristics, the type of soils and the vegetation; these, in turn, influence the agricultural activities which have a fundamental role in rural communities. Among the physical characteristics of the land, altitude has proven to be one of the main relevant variables due to its strong correlations with: climate, economic and agricultural activities, social and cultural habits. Figure 3.1 shows the spatial distribution of altitude across the national territory. Altitude directly influences the climate, having repercussions on average temperatures and on precipitations as already mentioned in section 3.5. For all these reasons, this variable is used as a reference to identify different zones corresponding to the highlands (Altiplano), valley and the lowlands (tropics, Amazon, and Chaco). Table 3.1 shows how the different zones have been divided, based on an arbitrary altitude classification. Hence, this criterion used for the classification is not an absolute rule for the establishment of regions across Bolivia [74].

Altitude Classification
Highlands > 3000 m.a.s.l
1500 < Valleys < 3000 m.a.s.l
Lowlands < 1500 m.a.s.l

Table 3.1: Criterion used for the altitude classification of the Bolivian territory.

3.7. Agriculture and Transformation Activities

The high heterogeneous differences in topographic characteristics and climatic zones makes the analysis of agricultural and transformation activities complex and extensive. For this reason, to simplify and summarize all main possible different situations across Bolivia the tables showed in the Figures 3.2, 3.3, 3.4, 3.5, 3.6 have been created, based on one of the most important national documents known as "Compendio Agropecuario" [74].

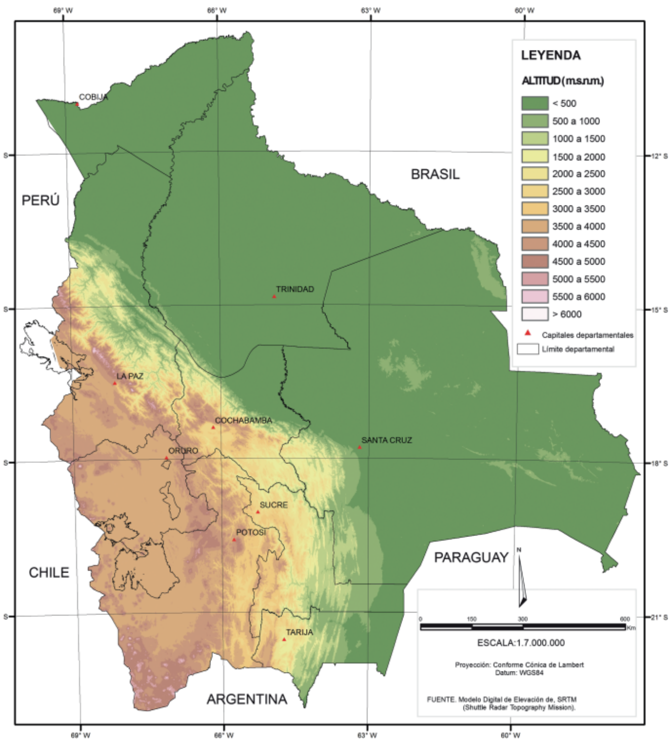


Figure 3.1: Bolivia's spatial altitude distribution.

Main agro-productive regions	Specific zone	General characteristics	Main agricultural products	Livestock	Irrigation	Main transformation activities
Highlands	Northern highlands	Primary production without transformation processes.	Potato, corn, bean, tarwi, peeled wheat, barley grain, quinoa, cane.	Bovine, sheep, goats, horses, pigs, rabbits and poultry.	Highlands concetrate 25% of total irrigation systems in Bolivia. Rainfall in this area is low, requiring a large amount of irrigation. However, the agricultural potential of the region is limited.	Obtaining camelid wool.
	Central highlands	Low-yield agricultural production associated with Andean crops and adapted cereals.	Low-yield agricultural production	Bovine (labour, meat and milk), camelids and pigs.		Cleaning of quinoa grains
	Southern highlands	Almost no agricultural skills, native livestock.	Quinoa, bean, potato, cabbage barley for livestock.	Camelids (lama). Extensive exploitation.		Flour processing

Figure 3.2: Agriculture and Transformation Activities: Highlands.

3.8. The Energy Sector Overview

The energy sector is almost completely nationalised, and it is headed by the Ministry of Hydrocarbons and Energy. In the period 2006-2020, primary energy production in Bolivia presented a growth rate of 15.41%, which is explained by the increased extraction of natural gas, as well as oil and derivates [24]. As a result of this trend, the total primary energy supply (TPES) is mainly dominated by natural gas which in 2020 represented 80.22% of total production. Since 2014, Bolivia has begun to diversify its primary energy production, incorporating alternative energies (wind and solar) to exploit its own huge potential in nat-

Main agro-productive regions	Specific zone	General characteristics	Main agricultural products	Livestock	Irrigation	Main transformation activities
Valleys	Valley headwaters	The predominant crop rotation includes potatoes and minor cereals.	Potato seed, garlic, bean.	-	Valleys concentrate 70% of total irrigation systems in Bolivia.	Flour processing (grain milling)
	Temperate valleys	Intensive nature	Corn, grain legumes, fruit trees, floriculture.	Bovine animals (milk)		Vegetables and fruits washing
	Mesothermal valleys		Corn ,onion, potato, sugarcane, peanuts, beans, vegetables especially tomato and fruit(peach, apple, grape and cherimoya).	Sheep, Creole goats, pigs and vacunos.		Milk production
	Yungas de La Paz	This area includes agricultural areas in the steepest terrain of Bolivia.	Coffee, citrus, subtropical fruits, rice, coca, stevia and possibilities for silkworm breeding.	-		Coffe roasting.

Figure 3.3: Agriculture and transformation activities: Valleys.

Main agro-productive regions	Specific zone	General characteristics	Main agricultural products	Livestock	Irrigation	Main transformation activities
Amazonia	Amazonia		Timber, Brazil nut, acaí, cacao.		No irrigation systems were registered in Beni and Pando because they are located in regions with higher rainfall	

Figure 3.4: Agriculture and transformation activities: Amazon (Lowlands).

Main agro-productive regions	Specific zone	General characteristics	Main agricultural products	Livestock	Irrigation	Main transformation activities
Gran Chaco	Sub-Andean Chaco	It has an untapped irrigation potential	Corn, peanuts, chili, tobacco, vegetables and fruits	-	Chaco concetrates 2% of total irrigation systems in Bolivia. It has expansion potential	Flour processing (grain milling)
	Chaco plains	The main area of exploitation is extensive livestock based on Creole cattle grazing and browsing meadows and native forests of xerophytic nature. However extraction rates and growth rates are generally low	Maize is the main crop covering almost 70% of the cultivated area. Soybeans, peanuts and beans follow in importance and together represent 20% of this area. Finally, tomato and onion.	The breeding of Creole cattle, preferably, is the most important.In addtion the breeding of pigs (mainly improved breeds). Horses in some areas represent an item of economic interest for the sale inside the country; the extensive raising of goats is a source of food security		

Figure 3.5: Agriculture and transformation activities: Gran Chaco (Lowlands).

Main agro-productive regions	Specific zone	General characteristics	Main agricultural products	Livestock	Irrigation	Main transformation activities
Tropical lowlands	Tropical foothills of Beni and La Paz	This area has great potential for sustainable crop systems	High value agroforestales crops and tropicales fruits	Bovine animals (meat)	Concentrates 3% of total irrigation systems in Bolivia. There is a reduced need for irrigation in this area due to humidity and rainfall levels	Flour processing (grain milling)
	Beni savannas	It is the largest beef producer in the country		Bovine animals (meat)		Vegetables and fruits washing
	Chapare	Agricultural activity is based on small mixed production systems. Forest management, agroforestry and timber production have great potential	Papaya, banana, pineapple, palm, citrus, rice, corn grain, yucca among others, together with coca cultivation	Bovine animals (milk)		Zafra
	Sub-humid Santa Cruz tropics	Dynamic commercial agriculture for exports has developed. Preparation of balanced foods that are intended for the feeding of birds and mono gastric animals	Extensive cultivation of sugar cane, soybeans, cotton, corn, rice, wheat and bean fruit crops (mango, pineapple, avocado, tamarind and citrus) and vegetables	Bovine animals (meat and milk)		Meat production

Figure 3.6: Agriculture and transformation activities: Tropical Lowlands.

ural resources. Even though the joint participation of biomass and hydro energy (renewable energies) has seen a significant growth rate (28.36%) in the period 2006-2020, in 2020 the percentage share of alternative energies in total production stated: 0.16% (wind and solar), biomass 5.71% and hydro energy 1.49% [24]. Figure 3.7 shows the TPES by source in 2020. Due to the COVID-19 pandemic, in the 2020, there was a decrease in the total supply of primary energy of 4% compared to 2019 caused by a lower use of fossil sources such as oil and natural gas.

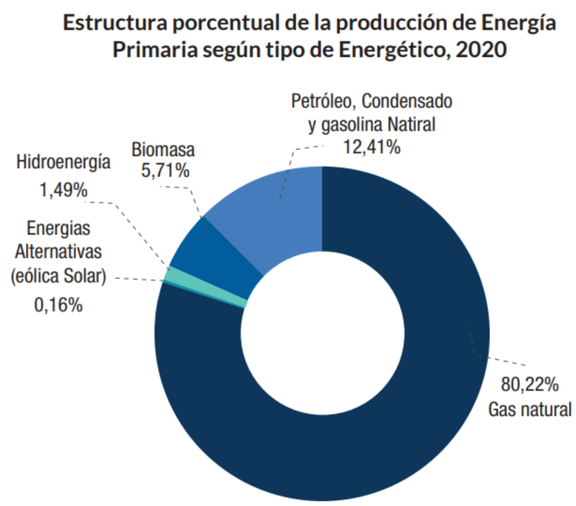


Figure 3.7: Total primary energy prodution per source.

Considering energy exports, the average from 2006-2020 was 73.72% out of the total primary energy, showing huge reliance on energy trades especially of natural gas towards Brazil and Argentina [70]. The remaining part of the TPES in 2020 was used for: final consumption (14.23%), power plants and self-producers (11.86%), natural gas treatment plants (3.90%) and other uses (0.39%). In addition, energy consumption experienced a significant growth of 65.08% in the period 2006-2020. In 2020, the main consumer of energy was the Transport Sector (48.96%), followed by the Industrial (25.34%) and Residential (17.26%) sectors [24].

The electricity sector in Bolivia was privatized in the early 1990s and was unbundled into generation, transmission, and distribution. Bolivia 's electricity sector consists of the National Interconnected System (SIN) and several off-grid systems (known as the "Aislados").

3.8.1. National Interconnected system (SIN)

The SIN is composed by generation, transmission and distribution sectors that together supply electricity across all the Bolivian departments mainly through high voltage transmission lines of 230, 115 and 69 kV. The system satisfies 96% of the total national demand and it is divided into four zones [56]: North (La Paz and Beni), Oriental (Santa Cruz), Central (Oruro and Cochabamba) and Sur (Potosi, Chuquisaca and Tarija). Figure 3.8 shows the overall layout of the system. Moreover, the generation sector comprehends: hydroelectric power plants, open-cycle natural gas turbines, combined cycle steam turbines, wind-onshore turbines, and PV power plants. Figure 3.9 shows the different contribution of each source of energy in the total electricity production of the country in 2020 [24].

There are two possible ways that allows the final consumer to participate in the electricity market. The first one implies being a regulated consumer, mainly represented by residential customers, that must rely on a distribution company for the provision of electricity. The second way involves being a non-regulated large consumer which are represented by big companies that are allowed to directly participate in the electrical market [56]. The electric consumption of the country is mainly residential, and it is highest in the Oriental area (37.8%) followed by North (24.3%), Central (21.4%) and South (17.2%) [24]. In addition, Figure 3.10 shows the different electricity consumption contribution per sector in 2020.

3.8.2. Isolated systems

In 2018, the Isolated Systems' installed power capacity was 388.69 MW, of which 65.6% corresponds to thermoelectric generation, 32.8% to biomass generation and 1.6% to hydroelectric generation and solar. In addition, these off-grid solutions are responsible of 6.8% of the total installed capacity, supplying around 10% of the total electrified households [56].

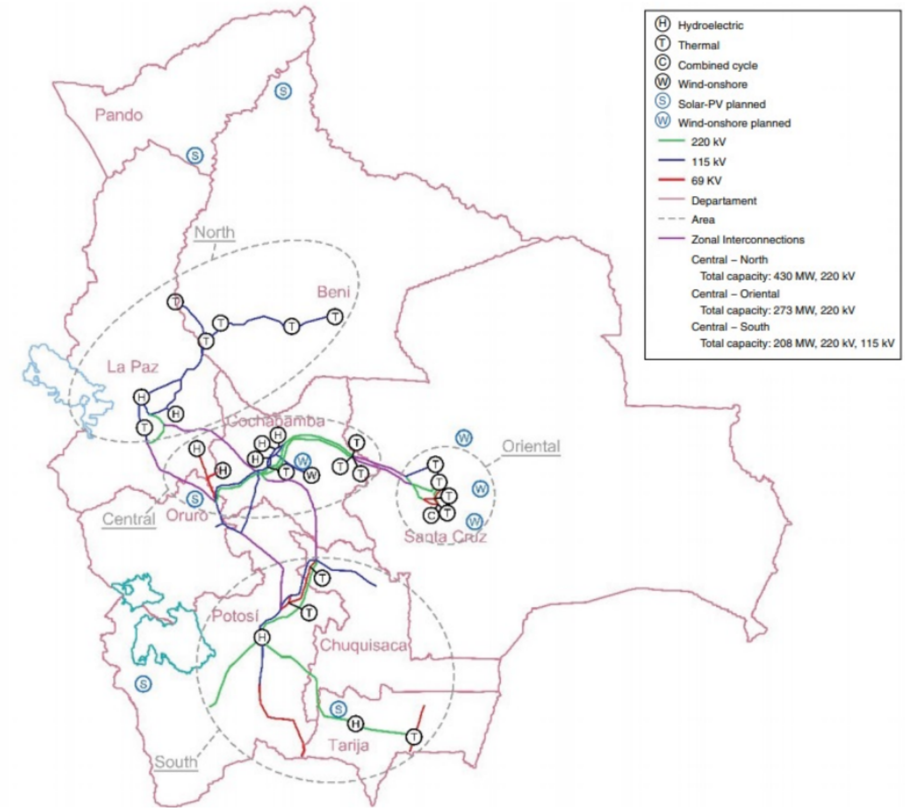


Figure 3.8: National interconnected system design.

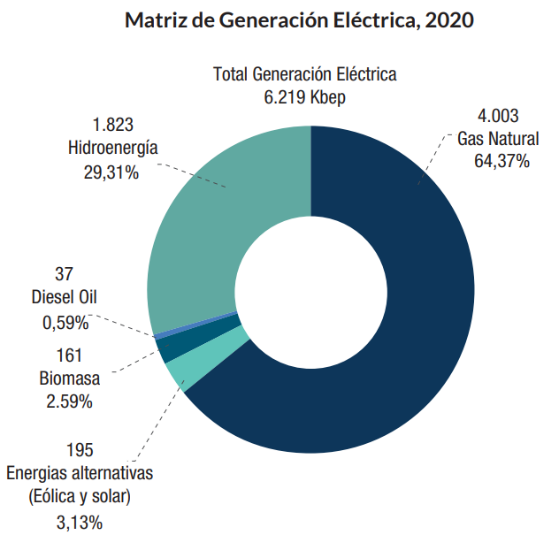


Figure 3.9: Electricity production by source.

The size of these systems can vary in a wide range that goes from kilowatts to megawatts of installed capacity. For this reason, it is possible to make a distinction between bigger and smaller isolated systems. The latter ones, referred as micro-grids, are characterised

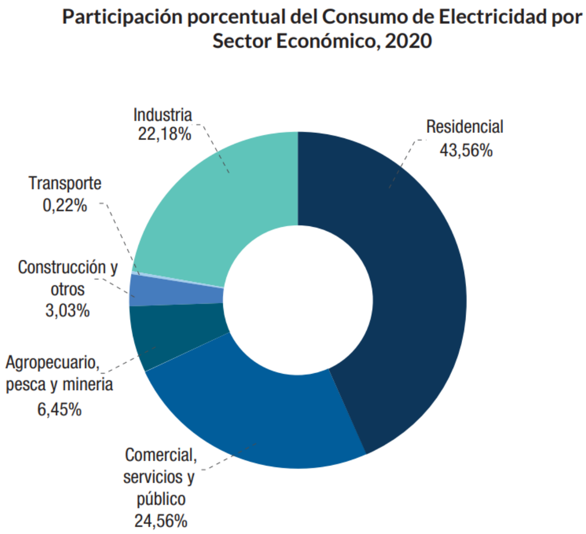


Figure 3.10: Electricity consumption per sector.

by an installed capacity in the order of kilowatts with non-regulated distribution network. On the other hand, the first ones are characterized by an installed capacity in the order of megawatts and with a regulated distribution network. Recently these types of systems have been attached to the main grid and they have been used as peak energy supply sources [70]. Moreover, if micro-grids are considered, only few systems have been installed in small off-grid communities. In the following table 3.2 are listed the overall functioning micro-grids in 2020.

Community	Installed capacity [KW]	n of Households
El espino	60	125
El sena	2018	426
El ramanso	166.5	175
Puerto villazon	156.4	95

Table 3.2: Installed micro-grids in Bolivia until 2020, taken from [11].

3.8.3. Electricity access

Among Latin American countries, Bolivia is one of the poorest. Even if important urban areas such as Santa Cruz and La Paz have good supply of energy services and are considered modern cities, in the majority of Bolivia's rural areas basic energy needs are not met. Regarding the average electricity consumption per capita per year, Bolivia stands far away from the world average and greatly below the value of OECD countries as showed in Table 3.3. The yearly average electricity consumption per capita gives an initial glimpse of the electricity access situation.

Country/Region	Elec. cons./pop [KWh/capita]
Bolivia	777
World	3265
OECD	7773

Table 3.3: Different distribution of yearly electricity consumption in KWh per capita [35].

Out of the total 11 million of Bolivian inhabitants 67.3% live in urban areas and 32.7% live in rural areas [23]. Starting from the early 2000s until the 2018 the electrification rate has significantly increased from an initial 64% to 93%. This trend shows great improvements and increasing efforts from the government that has set a goal to reach universal access to electricity by 2025 accordingly to the “Plan for Universal Energy Access 2010 – 2025” published at the end of 2010 [23]. However, the total electrification rate must be further analysed to examine the improvements made both in the rural and urban electrification process. Therefore, in the same period (from 2000 to 2018), the electrification rate in urban areas passed from 85% to 98% while in rural areas it went from 25% to 78%. These results, once again reflect the initial achievements of the national strategy that has invested both in grid extension and off-grid solutions. Figure 3.11 shows the real and forecasted trend regarding the total electrification rate evolution together with the two contributions of rural and urban areas.

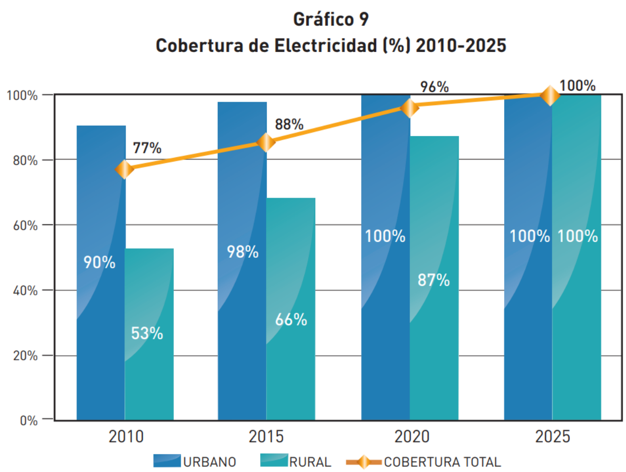


Figure 3.11: Real and forecast evolution of the electrification rate.

Figure 3.12 shows the level of electrification rate across all the Bolivian territory in relation to the population size of all the electrified communities. One important source of information for this purpose is the geo-referenced data from the latest National Census on Population and Households [38]. The database contains geo-referenced information of the number of households, electrification status, electricity source (grid, mini-grid, PV panel, diesel generator) and exact geographic location of all the 19300 communities located in Bolivia. [67]. Being located nearby high-voltage networks and being close to densely populated areas ,such as main cities, determines the probability of having a higher concentration of electrified communities.

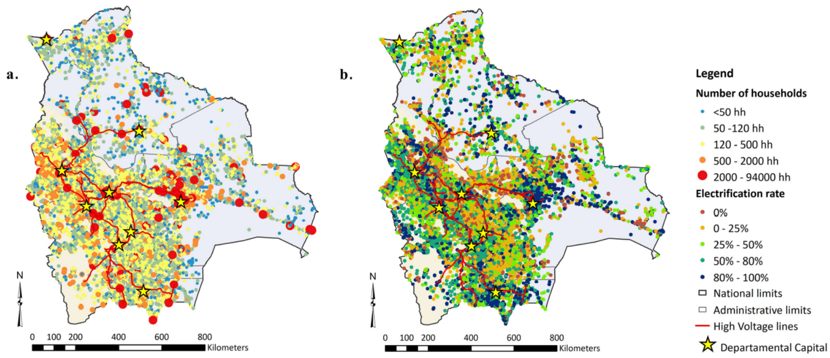


Figure 3.12: a. Population size classification. b. Electrification rate overview over the national territory. [38]

A preliminary assessment of the census database reveals that usually communities larger than 550 households are connected to the grid. On the contrary, smaller communities characterized by lower demand and located far away from the transmission lines do not allow a grid extension intervention and consequently have lower electrification rate. Indeed, the community size, its population density and its location directly affect the optimal least-cost electrification solution. It is possible to summarize the main logic for the selection of the most cost-effective solution as follows:

1. High demand, high population density and low distance from the grid favour grid extension.

2. Low demand, low population density and high distance from the grid (larger than 50 Km from the MV transmission lines) favour standalone systems.

3. High demand, high population density and high distance from the grid favours both isolated systems and grid extension.

Concerning the work thesis, the methodology presented is limited to the community size range where the micro-grid is the optimal solution for the electrification process: within a minimum of 50 households and a maximum of 550. In fact, below 50 households, the communities do not satisfy the requirements for the construction of micro-grids while above 550 the settlements usually already have a connection to the national grid. Figure 3.13 illustrates the location of the communities with the selected population threshold.

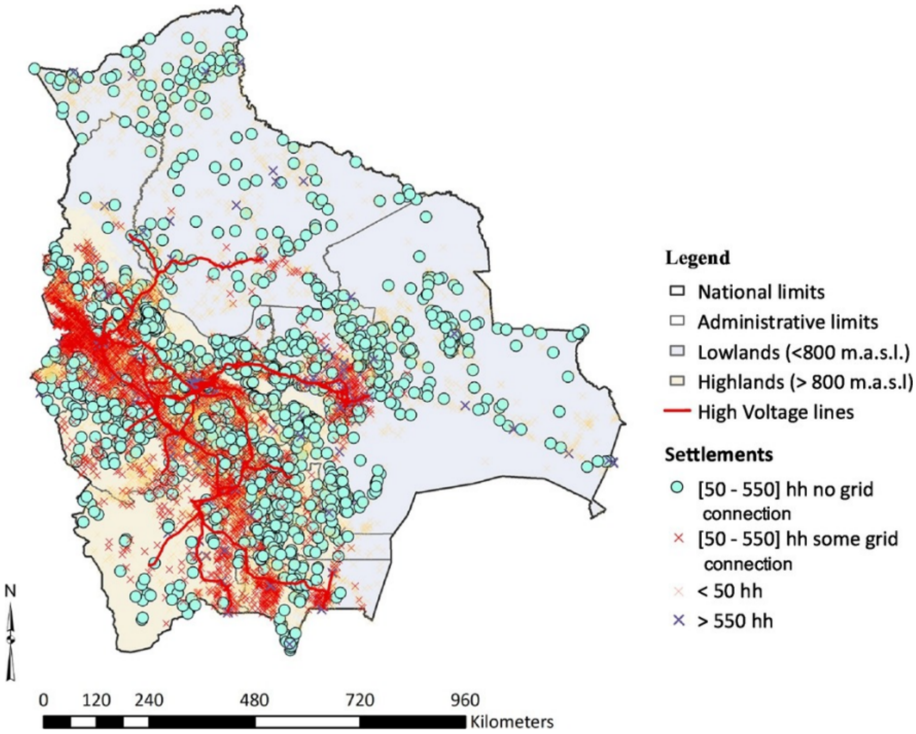


Figure 3.13: Distribution of connected and unconnected communities across Bolivia [11].

4 | Methodology

4.1. Rural energy demand modelling

The ability of forecasting the electric consumption of remote rural communities is one of the main challenges in the field of energy access projects [29]. One of the main barrier to overcome is linked to the uncertainty related to the load evolution over time of communities that do not have yet achieved energy access [63]. The evaluation of local energy needs is influenced by not easily predictable factors that can heavily influence the total load. Indeed, in the literature is common to encounter the presence of several studies that highlight the failure of energy access projects at meeting the demand as time passed [71],[78],[30], [43],[65].

One of the major challenges in energy access projects is accurately forecasting the electric consumption of remote rural communities [29]. One significant barrier to overcome in this regard is the uncertainty associated with the load evolution over time, especially for communities that are yet to achieve energy access [63]. The assessment of local energy needs is complicated by several unpredictable factors that can significantly affect the total load. The literature shows that many energy access projects have failed to meet the demand over time, highlighting the importance of addressing this challenge [71], [78], [30], [43], [65].

The main causes of incorrect sizing of off grid energy systems can be related to:

1. The necessity of relying on high quality and reliable data to reproduce the correct random behaviour of energy users, condition that does not apply in remote areas of developing countries. In fact, interview-based data are one of the most common sources of information used to calibrate input parameters. Hence, having data characterized by a significant degree of uncertainty prevents the possibility to model high resolution activity patterns [34]. Indeed, in the case of remote regions usually no monitoring can be performed before the actual electrification.

2. Unplanned connections of new energy users in the future, which can increase the total energy demand beyond the forecasted projections, as mentioned in [43].

3. The need to focus on energy planning purposes, rather than solely on load forecasting

[48]. This complex issue involves predicting future appliance usage and describing their activity patterns. Furthermore, the complexity increases when appliances that were not present at the beginning of the project are adopted by the population. For instance, in the design and development of a real microgrid system on Dongfushan Island, a significant error in energy consumption prediction arose due to intensive use of air conditioners [78].

All the listed arguments, in the end, determine an over or under sized energy system that cannot work in its optimal configuration for which it was originally designed. This is the reason why one of the main concerns is to ensure that the proposed systems can operate under a variety of energy profiles. Therefore, an ideal demand energy model for remote rural areas needs to be highly flexible and quickly able to adapt to future appliances and loads.

Ultimately, the factors listed above can result in an energy system that is either over- or under-sized, rendering it incapable of operating optimally as originally designed. Hence, it is crucial to ensure that the proposed systems can operate under a variety of energy profiles, taking into account the various sources of uncertainty [10]. Consequently, an ideal demand energy model for remote rural areas needs to be highly flexible and capable of quickly adapting to future appliances and loads [45]. This will enable the system to accommodate the changing needs of energy users and avoid being rendered obsolete by new developments in energy consumption patterns. The ability to adapt to these changes is essential for the long-term sustainability and success of off-grid energy systems in remote rural communities.

4.1.1. Techniques to model energy consumption

Most of demand energy models can be divided into two categories: top-down and bottom-up approaches [69],[65]. The terminology employed refers to the hierarchical role of input data as compared to the whole process of modelling. Top-down models usually use macroeconomic variables and indicators (GDP, employment rates, and price indices, climatic conditions, etc) to estimate and attribute general characteristics of energy consumption of entire sectors at a national level or at even larger scale. On the other hand, bottom-up approaches compute the energy consumption starting from specific communities or groups and then they use those results to represent entire regions with similar characteristics. Therefore, the general characteristics of the two models can be summarize as follows:

1. Top-down: It involves starting with a high-level view of energy demand with the aim of looking for an overall behaviour of energy consumption and supply across different sectors of an economy. These models focus on a balanced equilibrium between historical energy consumption values and estimations based on macro input variables. The

advantages are determined by the simplicity of the model and the reliance on historical data which is usually broadly available.Examples of top-down approaches compared or coupled with bottom up models are provided by [67] and [46]. However, since top-down approaches have a good prediction capability for small deviation from the already existing conditions, they are not able to forecast discontinuous technological advances such as a paradigm shifts. Moreover, the lack of detail regarding micro-level conditions, such as low technological characterization of energy systems, does not allow further key improvements in those areas.

2. Bottom-up: It involves the computation of energy demand starting at an individual level and then aggregating it to the sector or at regional level. This approach focuses on the high level of detail specific characteristics and behaviours of individual energy-using devices and processes, and considers factors such as technology adoption, behavioural patterns, and economic factors that influence energy demand. In fact, these models can reach a high level of technological characterization without relying on historical data and thus they can identify areas for end-use improvements as proved by [48] and [45]. The main disadvantages are related to the requirement of large amount of input data and that the computational effort can be resource intensive and time consuming.

Both bottom-up and top-down energy demand models can be useful tools for energy planning and policy, depending on the specific goals and needs of the modeler. It is often useful to use a combination of both approaches to get a more comprehensive understanding of energy demand as it has been explored by [46]. In fact, the study soft-links a stochastic bottom-up load curves estimation model, to a technology-rich energy system optimisation model.

4.2. Bottom-up modelling: RAMP

In the present study a bottom-up open-source stochastic energy model called RAMP is used [45]. The model builds on the work made by Mandelli et al. [48] that was specifically designed for rural applications where energy demands can be constructed relying on interview-based information. However, on field surveys, that are often the only information available, are affected by significant degrees of uncertainty preventing a high detail characterization of the activity patterns. To face this problem, RAMP is specifically conceived to deal with low level accuracy of input data, but, at the same time, it allows the generation of high-resolution energy load profiles. It is characterized by a stochastic method that can reproduce unpredictable random consumer behaviour by randomly varying parameters related to selfdeclared activity patterns such as the total time of use or the time frame windows of usage of electrical appliances.

4.2.1. Advantages over top-down models

There are several advantages that have determined to use a bottom-up approach for rural energy demand modelling such as RAMP. These advantages, extrapolated mainly from the literature review of [65] and all the previous works mentioned, are:

1. Accuracy: accurate and detailed representation of energy systems, technological options and specific characteristics and behaviours of individual energy-using devices.
2. Flexibility: possibility of customization to reflect the unique characteristics and needs of a particular rural area, such as population size and demographics, economic development, and social customs.
3. Insights: provide considerations into the factors that drive energy demand in rural areas, such as technology adoption, behavioural patterns, and economic factors. This information can be used to identify opportunities for energy development.
4. Decision-making: allows to inform decision-making about energy policies and programs in rural areas, such as the deployment of renewable energy sources or energy efficiency measures.
5. Open source: being an open-source software implemented in a Python environment, it enhances transparency, knowledge transfer, testability, customisability, and adaptability that are all crucial requirements for the energy modelling of remote rural areas.

Overall, a bottom-up approach as RAMP can provide an accurate and detailed understanding of energy demand in rural areas and can help policymakers and other stakeholders to make informed decisions about how to meet the energy needs of rural communities in a cost-effective and sustainable manner.

For practical purposes in the following sections the functioning of RAMP is briefly introduced. However, for a deeper description and details, see [45].

4.2.2. Three-layer Structure

Ramp is based on a three layers structure: i) the User type; ii) the User; and iii) the Appliance layers. The starting layer defines a set of arbitrary energy User types (e.g., household, schools, processing activities). Depending on specific situations and needs, it is possible to increase the level of detail subdividing the user type into different categories. For example, the generic household's user may require to be modelled in different ways based on income classes (e.g., high-income, low-income, or middle-income). Each user type is characterized by a number of individual users that are associated to a specific list of appliances owned by each one of those users. Therefore, the category of the User, identified by a specific number of the same total users, represents the second layer while the appliances, associated to that category and characterized by features and characteristics of their functioning, represent the third layer. Figure 4.1 gives a graphical picture of the above-mentioned concepts.

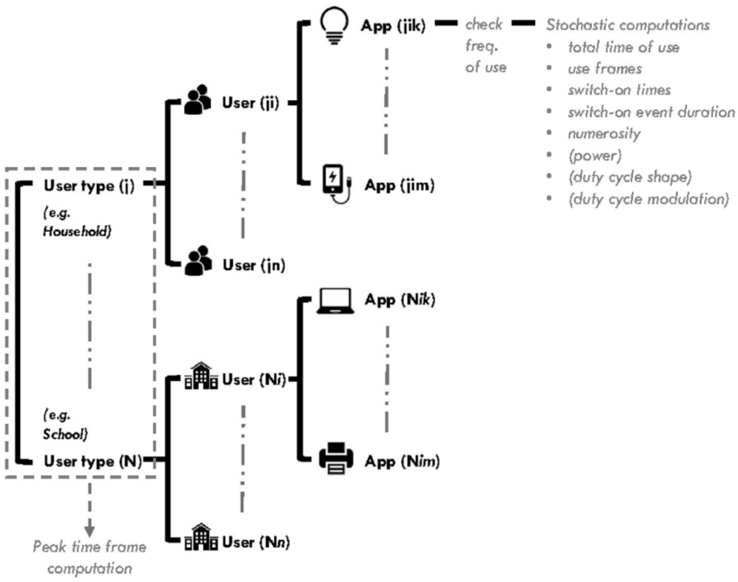


Figure 4.1: Graphical sketch of the three layers modelling structure.

This configuration, together with the stochastic algorithm, allows to independently model the behaviour of each jik-th Appliance. Hence, each individual user, belonging to the same category, has a different load curve even if characterized by the same appliances and activity patterns. In this way, it is possible to reproduce the intrinsic unpredictability of human behaviour. Every time that the model is run without changing the inputs creates a unique total load profile curve meaning that multiple model runs generate different total load profiles. Finally, to compute the total load profile, the model aggregates the independent load profiles of all the energy users. All the inputs necessary by the model are summarised in the table represented in Figure 4.2.

4.2.3. Optional features

In comparison with the previous model developed by Mandelli [48], RAMP proposes an expanded stochastic approach that further increases the degree of stochasticity and customizability adding new optional features for the Appliance layer. The following characteristics

User type and Users	
$\boldsymbol{Usertype_j}$	Name of the *User type* (e.g. "households", "commercial activities", etc.)
$\boldsymbol{n}$	Number of $\boldsymbol{Users_{ij}}$ (for $\boldsymbol{i} = 1 : \boldsymbol{n}$) within $\boldsymbol{Usertype_j}$
Appliances	
$\boldsymbol{Appliance_{jik}}$	Name of the *k-th Appliance* associated with the *j-th User type* and the *i-th User*
$\boldsymbol{m_{jik}}$	Numerosity of $\boldsymbol{Appliance_{jik}}$ (e.g. numerosity of "indoor light bulbs")
$\boldsymbol{P_{jik}}$ [$\boldsymbol{W}$]	Power absorbed by a single item of $\boldsymbol{Appliance_{jik}}$ (i.e. assuming numerosity $= 1$)
$\boldsymbol{tot\_use_{jik}}$[$\boldsymbol{min}$]	Total time of use of the $\boldsymbol{Appliance_{jik}}$ in a day
$\boldsymbol{t\_min_{jik}}$ [$\boldsymbol{min}$]	Minimum time that the $\boldsymbol{Appliance_{jik}}$ is kept on after a switch-on event
$\delta_{t\_min,\ jik}$ [%]	Percentage random variability applied to $\boldsymbol{t\_min_{jik}}$
$\boldsymbol{use\_frames_{jik}}$	Time frames in which a random switch-on of $\boldsymbol{Appliance_{jik}}$ can occur
$\delta_{frames,\ jik}$ [%]	Percentage random variability applied to $\boldsymbol{use\_frames_{jik}}$

Figure 4.2: Summary of the input data required by the model.

are the most important features used during the work:

1. Modular duty cycles: it allows to model pre-defined duty cycles and to assign different behaviours to those cycles depending on the time of the day. Hence, it is possible to easily model appliances such as a fridge that changes its energy consumption due to the variation of several parameters during the day. For example, temperature variation is one of the main variables that impacts on the shape and intensity of duty cycles.

2. Frequency of use: it allows to model appliances that are only used occasionally during the week such as mixers or irons.

3. Thermal appliances and random power regulation: It allows to set a percentage variation on the nominal power absorbed by thermal appliances. In such way, a further degree of variability is introduced that is especially useful to model appliances' behaviours that require power regulation thus reproducing highly random and subjective tasks, such as cooking cycles.

4.3. Sizing of microgrids

The electrification of remote areas is a significant challenge for many developing countries. Although national electrification programs aim to achieve nearly 100 % coverage, they face a major obstacle in connecting the last percentile of the population, which is typically composed of remote and isolated communities [33]. Extending the national electricity grid to these areas is the traditional solution, but it is not always feasible due to long distances, low energy density, and high costs. Fortunately, hybrid microgrid systems provide a promising alternative for electrifying isolated rural communities as discussed in chapter 1. These systems are small, localized power grids that can operate independently or be connected to a larger grid providing a sustainable and cost-effective solution for remote electrification. In fact microgrids can increase energy access, provide economic benefits, and reduce carbon emissions by combining multiple sources of energy, such as solar, wind, and diesel generators[62]. Therefore, they can be powered by renewable energy sources, non-renewable energy sources and storage systems with complementary operational characteristics.

Diaz et al. [30] demonstrated their potential by analysing 28 isolated microgrids and exploiting the synergies between their components. When components are optimally integrated, the resulting microgrid systems can offer superior performance and sustainability. Hybrid microgrids have the potential to offer energy at lower costs than traditional alternatives, given the right conditions. For example, Mentis et al.[50] used GIS techniques to calculate the cost of electrification in Nigeria, highlighting the significant advantage of hybrid solutions when diesel costs are high. In a related study, Nerini et al. [55] expanded on this cost model and analysed the impact of various factors on the levelized cost of electricity (LCOE) for each electrification option. Their findings provide valuable insight into the economic feasibility of hybrid microgrids and their potential to offer affordable, sustainable energy to remote communities.

4.3.1. Recent challenges in isolated microgrids modelling

Hybrid microgrids offer numerous advantages for remote electrification, but their planning and operation face several challenges:

1. Uncertainty in renewable energy potential forecasts [30].
2. Complex dynamics of rural electricity consumption, especially for future loads evolution [52].
3. Imperfect mathematical representation of microgrid components [59].

Therefore, the challenges facing hybrid microgrid planning and operation can be categorized into two types of uncertainty: parametric uncertainty and structural uncertainty.

Parametric uncertainty: relates to the long-term demand and renewable energy projections that models rely on. These parameters are typically represented as exogenous variables and can vary significantly depending on the location and community being served [77]. Changes in energy demand and consumption patterns can impact the sizing process, as demonstrated by Riva et al. [65], [64]. Failure to account for these factors can lead to important implications for the project's installed capacities and overall viability. Regarding long-term forecast of renewable energy availability, the study by Diaz et al. [30] shows that the fuel consumption of a hybrid system can vary significantly from one year to another depending on the renewable energy output during that period.

Structural uncertainty: arises from the need to balance the necessity for computational efficiency and accuracy with real-life relevance. In fact, microgrids components are often modelled using simplified mathematical formulations, such as constant efficiencies, or by neglecting technological constraints due to a lack of data or to lower the computational effort. This can result in inaccurate models and biased planning of the system [77]. For example, Linear programming (LP) is a popular method for microgrid optimization due to its low computational efficiency and ability to obtain the global optimum of large problems [63]. However, it cannot model non-linear or discontinuous component characteristics. Using LP optimization, diesel generators are often modelled without accounting for decreased part-load efficiencies or minimum load constraints, leading to overestimation of performance. On the other hand Mixed-integer linear programming (MILP) can address some of these limitations, but it requires high-quality data in terms of real-life and site-specific operation [59].

4.3.2. Techniques for optimization under uncertainty

To overcome these challenges, ongoing research and innovation are necessary to improve forecasting models, understand rural electricity consumption dynamics, and refine mathematical representations of microgrid components. By doing so, it is possible to unlock the full potential of hybrid microgrids and provide sustainable, affordable energy to isolated communities.

One approach for addressing demand and resource uncertainties is sensitivity analysis performed on uncertain parameters, as suggested by Brivio et al. [19]. Another approach involves using robust optimization, as explored by Khodaei et al. [42] even if microgrid components are still sized to meet the requirements of a specific scenario with a given demand and renewable energy time series.

Two-stage stochastic optimization is a useful approach for addressing uncertainty in microgrids. This method involves optimizing an objective function while accounting for set of constraints. The overall goal of the two-stage stochastic optimization model is to find the optimal variables in the first stage that will minimize the overall cost or maximize the overall benefit across all possible scenarios in the second stage. This framework is well-suited to microgrids, as demonstrated by Zhou et al. [79], who used a two-stage optimization problem to size a multi-energy distributed system. Additionally, a MILP two-stage stochastic programming model was employed in [76] to design a distributed energy system, revealing that demand uncertainty has a significant impact on system sizing while energy prices and renewable energy production have a relatively minor effect.

Research on two-stage optimization for microgrid sizing primarily focuses on accounting for uncertainty in demand and renewable generation. The goal is to design systems that can operate under various energy profiles, which are usually generated using statistical methods and historical data in the form of time-series. However, for remote regions, there is a high level of parametric uncertainty associated with these input data, as monitoring cannot be performed before the actual electrification, as already explained before.

4.4. A two-stage linear programming optimization: MicrogridsPY

MicrogridsPY [10] is the open-source tool used in this work to size microgrids. The tool is based on a two-stage stochastic optimization approach, which takes into account uncertainties in both the demand and renewable generation. The model is highly flexible, allowing for the adaptation of the model structure to meet specific formulation requirements based on the intended application.

The tool requires several inputs, including a load demand profile for a typical year over the selected time horizon, as well as the potential of renewable resources, selected to satisfy the demand, in terms of energy output. Additionally, techno-economic parameters are required for the selected technologies, including their specific costs, such as the specific costs of the back-up diesel generator and the cost of fuel, as well as other typical energy planning parameters like the discount rate and the cost of unmet demand. The time resolution of the model is customizable by the user and is typically set to one hour. MicrogridsPY is able to accommodate a variety of renewable energy systems, as long as the user can provide an appropriate energy time series for the selected technology. This can be achieved through the elaboration of resource availability data such as solar radiation, wind speed, or water mass flow rate.

The model's objective function is to minimize the Net Present Cost (NPC) of a hybrid microgrid. This includes the initial investment, as well as the annual operation and maintenance costs such as maintenance of the system and the purchase of fuel for the generators. The outputs of the model include the size of each energy conversion technology and the dispatch strategy for the microgrid, indicating the amount of energy produced by each technology at each time-step, along with other economic parameters related to the costs of the system. A summary of the main inputs and outputs is provided in Figure 4.3 together with a summary of the whole functioning of the model. For a deeper description of the functioning of the model see [10].

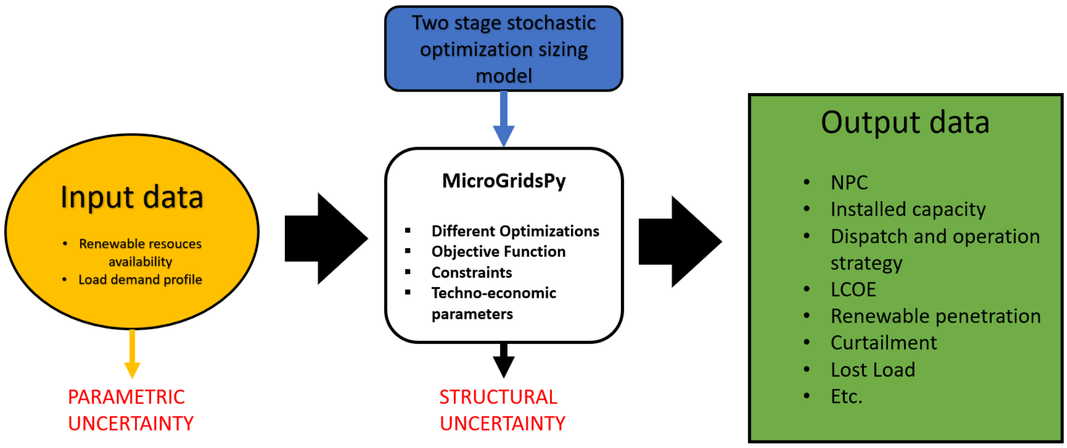


Figure 4.3: Summary of model's functioning.

4.5. Starting the Rural Energy Demand Estimation process

Once the significance of accurately assessing the demand and its relationship to key drivers of development needs has been acknowledged, also through the re-conceptualization of the energy sufficiency status (section 2.5), a step forward is made. Therefore, the effort moves forward to put into practice a methodology to forecast the electrical demand of non-electrified communities starting by thoroughly understanding their needs.

The current models for characterizing energy demand in rural areas, especially bottom-up approaches, require high-resolution input data regarding appliance ownership and usage patterns as previously mentioned in section 4.1. However, this data is often limited or missing, especially in developing countries, where data paucity is a major challenge for energy modelling [29]. This hinders the estimation of future load demand of un-electrified areas by energy planners and practitioners.

To address this crucial challenge, the proposed methodology aims to create a simple and practical tool by means of constructing load demand archetypes, allowing to perform a preliminary energy demand estimation in rural areas of developing countries. The archetypes have been designed to reproduce the entire Bolivian rural communities by making precise distinctions based on climate zones, poverty indicators, and household's number. This translates into a top-down approach based on three macro parameters coupled with a bottom-up energy demand model (RAMP) that allows a first round demand assessment of energy sectors in rural communities without the support of high data intensity.

The methodology is built upon the principle of energy sufficiency, as it has been crafted in section 2.5 and aims at describing the possible development path towards its achievement.

Therefore, it emphasizes how energy is closely linked to all sectors of the community, including education, health, social participation, and others. Moreover, a special focus is given to the relevance of agricultural and transformation activities that are often neglected when it comes to energy access projects.

4.5.1. The role of archetypes

Estimating the load demand for communities without prior electricity access [17] and tracking its evolution over time [63],[52] is a challenging task, particularly given the difficulties in gathering data from remote areas. In this regard, the archetype approach provides a simplified method for quick and easy first-round load estimates, functioning as an alternative to more complex and often less accurate load estimation techniques [17],[34].

This methodology could support a rapid identification of the most suitable locations, where more detailed and thorough assessments can start, improving the accuracy and efficiency of electrification planning [68]. For example, it will be coupled with sizing tools such MicrogridsPy giving useful information that allows to quickly identify priority strategies at national level. In fact, its low computational and financial requirements, along with its ease of use, and possible integration with Geospatial Electrification Modelling through Geospatial Information Systems, could support the formulation of cost-effective electrification strategies to meet different energy demands in rural areas. Furthermore, the archetype approach is meant to be flexible and adaptable, with the ability to adjust to changes in energy resources, demands, and local constraints, making it reusable in other contexts and countries.

4.5.2. Procedure Description

The following sections will describe the reasoning behind the construction of a set of load demand archetypes for different categories of rural users. Such archetypes are created through a synthesis of diverse sources including: field visits, literature reviews, and insightful information obtained from grey literature such as reports from the Bolivian government and international organizations on energy usage in rural areas.

It has been decided to divide the Bolivian territory into three regions, considering the altitude as the first important driver that could determine differences in the modelling of electrical demand (see section 3.6). In fact, altitude has proven to be one of the main relevant variables due to its strong correlations with: climate, economic and agricultural activities, social and cultural habits. Therefore, this study considers: the Bolivian highlands (HL), lowlands (LL) and valleys (VA) regions as they have been defined in section 3.6.

The proposed archetypes aim at modelling the complete structure of a community, encompassing the residential, community services, and IGAs sectors. In addition to altitude, poverty-related conditions and community size are also considered as variables that impact the community composition and, in turn, the total electrical load. The resulting archetypes are valid at national level providing a comprehensive understanding of how the electrical demand can vary based on different combinations of the three primary drivers considered. Figure 4.4 proposes a summary of the procedure described in the following sections.

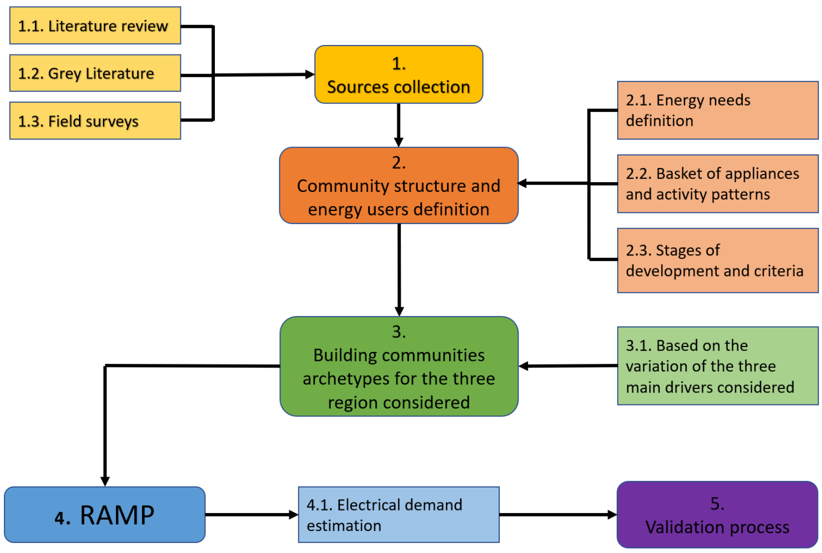


Figure 4.4: Flow diagram of the procedure.

4.5.3. Main goals

This initial approach is mainly focused on the following objectives:

1. Establishing relevant criteria for constructing a set of archetypes that accurately reflect the structure, characteristics, energy services, appliance ownership, and fundamental needs of rural communities.

2. Modelling the evolution of electricity demand when rural communities experiment a growth path, improving the living conditions towards a 'energy sufficiency state'.

3. Exploring the effects of an improved energy access, considering different community sizes, regions, and poverty-related conditions.

4.5.4. Main drivers of demand variation

As already mentioned, the methodology is based on an archetype approach. Every archetype is representing a community whose structure is characterized by specific characteristics determined by three main drivers. The composition of the archetypes is thus determined by:

1. The level of unsatisfied basic needs (UBN), which serves as the poverty indicator chosen as reliable and available [22]. In Latin America, the Unsatisfied Basic Needs method has brought an important contribution to identification of certain critical deficiencies of the population and the characterization of the poverty. It was introduced in the early 1980s to take advantage of the information on censuses, demographics and housing, in the characterization of poverty. Under this method, a series of census indicators are chosen to determine whether or not households meet some of their main needs. Once the satisfaction or dissatisfaction of these needs has been established, "poverty maps" can be constructed, which geographically locate the deficiencies noted.

2. The altitude that has proven to be one relevant due to its strong correlations with: climate, economic and agricultural activities, social and cultural habits. Therefore, this study considers: the Bolivian highlands (HL), lowlands (LL) and valleys (VA) regions as they have been defined in section 3.6.

3. The community size that translates into the total number of households. The methodology presented is limited to the community size range where the micro-grid is the optimal solution for the electrification process: within a minimum of 50 households and a maximum of 550. In fact, below 50 households, the communities do not satisfy the requirements for the construction of micro-grids while above 550 the settlements usually already have a connection to the national grid [11].

Each of these drivers influence the energy sector composition of the communities that are going to be modelled. In the following sections, it will be explained how these factors determine those variations.

4.5.5. Building blocks:energy sectors and users

Three main energy sectors are identified for the modelling of the community's structure: residential, community services and income generating activities (IGAs). Within each sector different users can be identified: each one of them is characterized by a list of appliances and specific activity patterns. However, the same energy user may be characterized by different features depending on the region considered. For example, climate differences can influence the list of appliances or the activity patters of the appliances itself. Table 4.1 presents all the

Sector	User	Type
Residential	Household	Low consumption households High consumption households
Community services	Medical centre	Health post Health center
	School	School A School B School C
	Public infrastructure	Public lighting Sports field/coliseum Church Water supply system
IGAs	Agriculture and livestock	Irrigation system Transformation activities
	Commerce	Grocery store Restaurant Workshop Entertainment (karaoke, bar)

Table 4.1: Energy sectors, users and types classification.

defined electrical users, that are used as building blocks for the construction of different communities.

The electrical demand modelling is made using the RAMP tool. For this reason, the energy user's definition has to be made according to the requirements of the energy model described in the Section 4.2. Moreover, the energy users are not representative of individuals or people, but instead the term refers to an entity that consumes electricity such as a household, a school or a particular business activity.

To understand the modelling of each energy user, the following sections 4.5.8, 4.5.9, 4.5.10, are focused on the description of each individual energy sector .

4.5.6. Appliance ownership and activity patterns

The importance of understanding the patterns and levels of appliance ownership in rural areas of developing countries cannot be overstated. It is crucial for energy access projects to take into account the appliance ownership and usage habits of individuals in these areas to ensure that the provided energy access has a meaningful impact on the lives of the people in these communities. However, the lack of available and reliable data regarding this topic still remains a challenging issue [29]. In fact, this work deals with a significant gap in the literature regarding the activity patterns and appliance ownership of some energy users, particularly community service users and IGAs. Due to the absence of data, assumptions are often made to identify the time windows and total duration of appliance usage. These assumptions are based on other works (listed in Table 4.2) or on the compatible working windows of other appliances, relying on empirical and practical reasoning.

Sector	User	Field surveys	Grey literature	Scientific literature
Residential	HI & LI	El Espino, El Sena Raqaypampa	[37] [25]	[11] [45]
Community services	Health post Health center		[28]	[45]
	Education facilities (type A,B,C)		[21]	
	Public lighting & water system		[25]	
	Sports field & church			
IGAs-agri	Irrigation system		[27],[26]	[73]
	Small scale diary industry	Cochabamba municipality		[72]
	Quinoa processing		[5]	[73]
	Cereal processing		[39]	[73]
IGAs-non-agri	Restaurant workshop entertainment grocery		[39] [53] [54]	[73]

Table 4.2: Sources collection.

As previously explained, generating bottom-up demand curves through the RAMP tool requires associating a specific number of appliances with each user type. To accomplish this, Table 4.2 lists all the sources utilized for the modelling assumptions related to energy user appliance and activity patterns, which align with the requirements of the RAMP tool. The table provides a comprehensive reference for the assumptions made in the methodology, enabling greater transparency.

Despite the crucial role of appliance ownership and activity patterns in demand characterization, this work does not focus exclusively on this field, as it would require extensive research. On the other hand, this methodology is built in such a way that could be further improved to overcome its own limitations. For example, an approach to enhance the methodology and better inform load prediction could be to integrate a database of observed consumption patterns in recently electrified communities. Therefore, the methodology could benefit from a reliable source of harmonized data, which can serve as a valuable asset for energy planners, in order to improve the quality of input data [68].

4.5.7. Stages of development: four archetypes structures

To explore the impact of enhanced energy access, it has been necessary to construct a hypothetical development pathway towards energy sufficiency for rural communities. For this purpose, with the size and location of a village fixed, the development process has been designed by a reduction in the levels of unsatisfied basic needs (UBN), which serves as the poverty indicator chosen as reliable and available [22].

Hence, based on UBN levels the composition and characteristics of the energy sectors of the community are going to change as showed in Figure 4.5. The UBN levels selected for each step of development are related to an existent approach with which rural Bolivian municipalities can be classified.

		Energy Sectors			
Archetype	UBN (%)	Residential	Community services	Agricultural IGAs	Non-agricultural IGAs
1	[100;96]	HI + LI households	NO	NO	NO
2	[96;90]	HI + LI households	Public lighting + water supply system	NO	Grocery store + restaurants
3	[90;70]	HI + LI households	Public lighting + water supply system + school	Irrigation system	Grocery store + restaurants
4	[70;56]	HI + LI households	Public lighting + water supply system + school + hospital + church + sport centre	Irrigation system + transformation activity	Grocery store + restaurants + entertainment + workshops

Figure 4.5: Four archetypes of community's stages of development .

The starting point is represented by an extremely poor rural community that is characterized with a poverty level higher or equal to 96 % UBN in Bolivia. In this stage, the community structure is assumed to be only composed by the residential sector. In the second stage modelled, the poverty status decrease until rural poor condition, represented by levels of UBN between 96% and 90%. This causes the appearance of some basic community services and IGAs users such as public lighting, water supply, grocery stores and small restaurants. The third community structure archetype adds up additional energy users encompassing irrigation and educational facilities representing a level of UBN between 90% of 70% that is the average condition among rural communities in Bolivia. Finally, the fourth possible community backbone structure for the energy sectors composition represents the achievement of the energy sufficiency status. In this case, the minimum level of UBN considered is 56% which is close to the highest poverty rate in urban areas.

4.5.8. Residential sector archetypes

According to the Electricity Authority's 2020 Statistical Yearbook [1], the residential sector accounts for the largest part of the national electricity demand with 43,56% of the total. This shows that the residential sector is expected to have a huge contribution in terms of total electrical demand inside rural communities. Therefore, it is crucial to model correctly the electricity use of households and its correlated complexities.

The configuration of the residential rural sector is made taking into account two categories of households: low-income and high-income households. The first one is associated with low electricity consumption and the ownership of few low power appliances. The latter, instead, is associated with high electricity consumption differentiating from the low-income category mainly for the usage of modern appliances such as refrigerators.

It is important to explore how, within the methodology thought process, the three main drivers affect the characteristics and composition of the residential sector since each of those will determine a variation in the load curve.

Altitude: each region is considered to own a different basket of appliances where different cultural habits and climate conditions have developed different activity patterns of usage of electrical appliances. For instance, the energy consumption of a refrigerator can vary based on the average temperature range in the three regions being considered, as the cooling cycles will be modelled differently in each location.

Size of the community: by using the total population as a starting point, the estimated number of households can be calculated by dividing the population by the average number of people per household. In rural areas this number is assumed to be 3,1 according to the Household Survey 2016-2017 [36]. However, the number of households only affects the size of the residential sector and does not impact its behaviour in any other way. As a result, each household is considered to be independent of others.

UBN: the UBN percentage determines the proportion of households that are classified as high-income (HI) and low-income (LI) within the community. The poverty level reflected by the UBN is used to approximate the percentage of LI households in the total population. For instance, if the UBN level in a rural community is 70%, it is assumed that 70% of the households in that community are classified as having low electrical consumption while the rest are considered to be HI households.

4.5.9. Community services archetypes

The community service energy sector focuses on the satisfaction of basic needs for: education, good health, clean water availability and other recreational activities to enhance social life. To deliver these services, appropriate infrastructures are needed including hospitals, schools, drinking water supply systems, sport facilities, public lighting and churches. As already done with the residential sector, it is fundamental to explore how the three drivers influence the modelling of the community services sector.

Altitude: Government-mandated norms and standards for the community sector are uniform across the country, and as a result, altitude will not have any effect on the composition and characteristics of the energy users of this sector. This means that the list of appliances and the usage patterns associated with each service will remain unchanged. The only variation across different regions considered is in the behaviours of thermal appliances, which is determined by the average temperature of the targeted area.

UBN: The level of UBN in a community determines the composition of its energy sectors. Based on a specified level of poverty, the selection of energy users for each energy sector follows the rules outlined in Figure 4.5. Consequently, each community service facility will be included in the community structure only if a certain UBN threshold is met.

Size of the community: Based on the levels of UBN achieved, that determines the presence of the energy sector users as explained in Figure 4.5, a selection of various types of facilities will take place using specific criteria for different services. The criteria assumed for this methodology are explained in the following sections for each type of facility considered and summarized in Table 4.3.

Sector	**User**	**CRITERIA**
Community services	Health post	500-1000 inhabitants
	Health centre	> 1000 inhabitants
	Public lighting	1 lamp post per every 10 households
	Colisium/Sports field	1 per community with more than 500 inhabitants
	Church	1 per community with more than 500 inhabitants
	Water Supply System	1 per 100 households
	School A	< 100 inhabitants
	School B	100-500 inhabitants
	School C	> 500 inhabitants

Table 4.3: Community services user criteria.

Health facilities

For instance, the "National Norm for the Characterization of Primary Health Care Facilities" [28] sets guidelines and standards for the availability of healthcare facilities in rural areas, including infrastructure and equipment requirements. The type of health facility required varies based on the size of the community. For communities with a population between 500 and 1000, a "health post" is mandated, while for those with a population between 1000 and 10,000, a "health centre" with the capacity for hospitalization is required. If a community has fewer than 500 residents, it must be within a two-hour driving distance from both low and high-capacity healthcare facilities. Therefore the equipment ownership data per facility type was collected.

Educational facilities

With regards to education, three types of schools have been identified as the most common in rural areas, based on community size. Type A schools are small multi-level establishments located in the smallest and most remote communities with a population of less than 100 people. Type B schools have a larger number of classrooms and offer a range of instruction from primary to secondary education, with double-shift operation for communities with a population between 100 and 500. Type C schools are well-equipped educational institutions that can accommodate a greater number of students, typically in larger communities near cities or major roads when the population exceeds 500 [28]. Access to educational facilities remains a significant challenge for those living in rural communities. For example, education coverage still stands at 73-83% in the lowlands, indicating that significant improvements are still possible despite recent progress [28].

Drinking water supply systems

The type and characteristics of drinking water systems are influenced by the availability of water resources and the terrain in which the community is located. However, a standard water supply system has been chosen for each type of community in this study [25], as the modeling of these systems is not the primary focus. Future research could focus on a more in-depth characterization of water supply systems, as they are crucial for the health and well-being of rural communities, as emphasized by the Sustainable Development Goal 6 (SDG 6).

Public lighting

The presence of streetlights in rural communities is guided by the standards set forth in a document published by the energy ministry [25], which provides guidelines for the implementation of energy access projects. Accordingly, the guideline states that a streetlight must be installed for every 10 households in a community.

Church and sport fields

In recent years, the availability of sports facilities in rural communities has increased due to government health policies, as the Supreme Decree No. 1868 of the 2014 testifies [51]. As a result, only communities with a population greater than are considered to have sports facilities. The same consideration applies to the presence of churches.

4.5.10. IGAs archetypes

Income generating activities are defined as responsible for income increase or productivity growth. Neglecting the energy needs of IGA increases the risk of energy marginalization in rural communities, leading to greater energy inequality and a significant underestimation of the communities' total energy needs [57].

This energy sector is divided into agricultural and non-agricultural activities. Non-agricultural activities include grocery stores, restaurants, workshops, and enterteinment businesses , while agricultural activities encompass irrigation systems and the processing of agricultural products. As already done for the other two sectors, it is fundamental to explore how the three drivers influence the modelling of IGAs.

Altitude: In this case altitude influences the criteria for the type and numerosity of energy users in a community. With a fixed community size and a UBN level that allows for the presence of IGA energy users, altitude affects the number of non-agricultural activities, reflecting the unique characteristics and preferences of the region. For instance, the number of grocery stores in the highlands is higher compared to the lowlands, even though both communities considered have the same UBN and population size. The same principle applies to the modelling of the number of irrigation systems. Additionally, for the three regions considered, a specific processing activity that is unique to that region has been included in the modelling. Hence, only three processing activities are modelled and each one of them cannot be present in the other regions.

UBN: The level of UBN in a community determines the composition of its energy sectors. As already mentioned, based on a specified level of poverty, the selection of IGA energy users follows the rules outlined in 4.5. Consequently, each community IGA user will be included in the community structure only if a certain UBN threshold is met.

Size of the community: The numerosity of IGA users is influenced by specific regional criteria. However, the overall numerosity is also considered proportional to the total population, calculated using an empirical formula. For instance, considering that in the highlands the number of grocery stores is one every 25 households while in the lowlands is one every 30.

The criteria assumed for this methodology are explained in the following sections for each type of IGA considered and summarized in Table 4.4.

		CRITERIA	CRITERIA	CRITERIA	
Sector	**User**	Highlands	Valleys	Lowlands	Unit
IGA-agri	Irrigation systems	1 every 30	1 every 22	1 every 18	HH
	Transformation activity	1 every 200	1 every 200	1 every 200	HH
IGA-non_agri	Grocery store	1 every 25	1 every 25	1 every 30	HH
	Restaurant	1 every 30	1 every 30	1 every 30	HH
	Workshop	1 every 80	1 every 70	1 every 60	HH
	Entertainment	1 every 100	1 every 80	1 every 60	HH

Table 4.4: IGAs user criteria.

Non-agricultural IGAs

Non-agricultural IGAs are influenced by both endogenous and exogenous factors and reflect the local idiosyncrasies of each region. For instance, certain areas in the lowlands, like the Beni region, have a higher concentration of recreational and food businesses [73]. Taking into account these regional variations is crucial for modelling, but it can also be a complex task due to the limited availability of this type of data. For this reason, the empirical formulas presented in Table 4.4 are just an initial attempt that aims at capturing the frequency of appearance of these businesses, based on [73], [54], [53].

Irrigation systems

In rural areas, there are various types of irrigation systems, some of which require electricity while others do not. Most of the irrigation relies on flood-gravity techniques, which cover around 97% of the irrigated land. However, there has been an increasing adoption of modern irrigation methods such as sprinkler or drip irrigation, which account for the remaining portion. Based on the "Irrigation Development National Plan" [26], the majority of requested irrigation projects in rural areas are of micro or small typologies. To simplify the analysis, it is assumed that rural villages are more likely to have small or micro systems that include an electric pump and a drip irrigation system. It is also assumed that each system can cover up to ten acres of cultivated land.

The total number of irrigation systems is determined by a function of the population, taking into account the number of households and the region they belong to. This correlation is derived from a simple analysis of irrigation system databases, specifically by studying the distribution of irrigation systems across Bolivia [27]. The variation in the number of irrigation systems aims to reflect differences in climatic conditions and rainfall volume, as well as the significance of the agribusiness industry in the region, as previously discussed and analysed in section 3.5. However, as the primary focus of this study is not on modelling these systems, and due to the potential complexity of such task, it is suggested that future research could explore deeper into characterizing these systems.

Transformation activities

Agricultural product transformation can boost economic growth, diversifying the source of income while increasing the electricity consumption due to the need of processing equipment and machinery [39]. Among governmental and non-governmental support programs, the provision of equipment is often included to support the processing. However even after access to electricity, the thriving of processing products remains challenging.

In this context, one processing activity has been selected for each region and will only be introduced once the energy sufficiency status is achieved. Extensive analysis, based on [74], was conducted to select relevant processing activities for each region and for the national context. Therefore, Quinoa processing was selected for the highlands, cereal processing for the lowlands, and a small-scale dairy industry for the valleys.

The seasonal behaviour of quinoa and cereals must be taken into account for these processing activities, and therefore these activities are only modelled during the harvest period, which typically spans from July to October [74]. Additionally, to determine the number of processing units, it was decided to introduce one unit for every 200 households, based on [39], with the exception of the milk dairy industry, which has a fixed assumed number of one unit.

Focus on agricultural IGAs and their link to SDGs.

The development of income-generating activities (IGAs) has the potential to align with Agenda 2030 and the Sustainable Development Goals (SDGs). As the SDGs are highly interconnected, it is important to consider how enhancing agricultural and transformation activities in rural communities could promote multidimensional growth. Therefore, it is essential to pay close attention to the possible impacts of IGAs on local communities and to classify those impacts according to the relevant SDG sphere of influence. This is why this thesis focuses on IGAs and the modelling of processing activities, as they offer significant potential for positive impacts on rural communities and alignment with the SDGs.

In addition to the potential positive impacts of income-generating activities (IGAs) on rural communities and alignment with the SDGs, this thesis also aims to fill a gap in the literature by exploring the modelling of processing activities. This is an area that has not been extensively studied, despite the significant potential for promoting economic growth and social well-being in rural areas. By focusing on this specific aspect of IGAs, this thesis aims to provide new insights and contribute to a more comprehensive understanding of the potential of IGAs to support sustainable development.

The following paragraphs aim to explore the potential interconnections between IGAs and the SDGs, creating a probable systems dynamic that could trigger a positive feedback loop which starts with the SDG 7.

SDG 7. Access to energy, especially electricity, is critical for enabling the use of electrical equipment in income-generating activities (IGAs), including agricultural and processing activities. Therefore, achieving SDG 7 through energy access projects can be viewed as a vital tool for satisfying other SDGs. This sets in motion a system dynamics approach to understand the complex electricity development nexus. It is important to recognize the concept of energy access as an instrumental right, meaning that it is a means to enable and support the realization of fundamental human rights, rather than a fundamental right in itself. This perspective highlights the significant role that energy access can play in driving progress towards sustainable development goals.

Main direct impact: SDG 2.3. As advancements are made towards achieving SDG 7, the availability of electricity can significantly increase the probability for income-generating activities (IGAs) to develop and flourish. In the best-case scenario, this could lead to progress towards achieving other SDGs, particularly SDG 2.3, which aims to double agricultural productivity and incomes of small-scale food producers. Access to electricity enables the use of modern technologies and equipment, improving efficiency and productivity in agricultural and processing activities. As a result, rural communities can potentially increase their income and food security, thus contributing to the achievement of SDG 2.3.

Second main direct impact: SDG 8.2. The progression and achievement of SDGs can have chain reactions and multiple parallel consequences. For instance, by increasing agricultural productivity among small-scale food producers, it becomes possible to move towards higher levels of economic productivity through diversification, technological upgrading, and innovation, as outlined in Goal 8.2.

Coming back to the SDG 7. Consequently, these improvements can create a reinforcing loop that supports the growth of electricity demand, restarting the cycle and fostering local socio-economic changes that can impact other SDGs, such as reducing poverty levels (Goal 1) and decreasing hunger (Goal 2). The systems dynamics related to the consequences of electricity access are complex and difficult to establish due to the influence of individual behavioural choices and multiple socio-economic system variables [61]. The ultimate goal should be to unlock a positive reinforcing loop that starts with the need for electricity and ends, after several steps, with sustained growth in electricity demand due to global economic growth.

Hence, as indirect possible positive impacts of the mentioned process can extend to other SDGs as well:

1. Improved water management for irrigation and sanitation purposes (SDG 6).
2. Enhanced infrastructure in the community (SDG 9), particularly in relation to goal 9.3 to increase small-scale enterprise access to financial services and value chains.
3. Reduced inequalities within and among countries (SDG 10), with specific implications for goals 10.1, 10.2, and 11.a. These impacts further demonstrate the interconnections of the SDGs and the potential for a reinforcing loop of positive change. However, the complex and multi-variable nature of this process highlights the need for a systems approach to better understand and exploit these potential benefits.

4.5.11. Describing the energy sufficiency modelling

As previously stated, the fourth stage of development represents the achievement of energy sufficiency through the re-conceptualization delineated in section 2.5. Therefore, it's crucial to thoroughly examine the reasoning behind the community structure's composition and characteristics that reflect this status since it represents a central aspect of the electrical demand characterization and thus an essential component of this work. Firstly, achieving energy sufficiency for rural communities is assumed to correspond to reaching poverty rates similar to those found in urban areas, in terms of UBN levels.

Secondly, the selection of the energy users that compose the community structure needs to follow the one outlined in the table 4.1. To this regard, the energy users' type and number are maximised to ensure that the basic needs of the entire community are met, promoting economic and social development, following the criteria associated to the size of the community. In fact, the size of the community plays a key role in determining the composition of energy users, as certain types of energy users may only be feasible for communities of a certain size. For instance, the same community located in the same region that achieves energy sufficiency will have a different number and type of energy users depending on the total number of inhabitants modelled.

Finally, it is important to explain how the energy sufficiency lines have been established to meet the basic needs for each energy sector. It should be noted that the majority of these considerations align with the standards and norms established by the government, as discussed in subsection 4.5.10,4.5.9,4.5.8, and are therefore applicable nationwide, regardless of regional differences. In the following paragraphs are thus explained the reasoning followed for each energy sector.

Residential sector. Among national policies aimed at promoting the use of electricity in the less advantaged communities, the Dignity Tariff has been established for residential consumption, which offers a 25% discount on the total bill for households that consume less than 70 kWh per month [75]. However, this threshold has been reduced to 50 kWh per month for rural communities due to their typically lower levels of electricity consumption. The government considers the value of the dignified tariff to represent a decent level of electricity consumption, making it a useful point of comparison for future analysis. For this reason, to ensure that basic needs are met, the level of electricity consumption corresponding to the value of the Dignity Tariff for rural areas [75] , which is greater than 50 kWh per month, has been selected as a reference point. Therefore, the dignified tariff represents the threshold that must be met to achieve energy sufficiency for households.

Community services sector. The presence of the following energy users is considered mandatory for achieving energy sufficiency, provided that the community size threshold necessary to support the facility is met:

1. One type of educational establishment (type A, B, or C), as discussed in [21], is considered sufficient.
2. One type of health facility (Health Centre type or Health Post) is considered sufficient based on "The National Norm for the Characterization of Primary Health Care Facilities" [28], which also outlines the minimum infrastructure and equipment requirements.
3. One "coliseum" sports centre and one church are required.
4. Public lighting and water supply systems must be provided in proportion to the population, following their respective criteria.

IGA sector. The presence of the agricultural and non-agricultural activities as explained in subsection 4.5.10 is considered as a minimum standard to satisfy basic needs for dignified work conditions and economic activities. Therefore, it is assumed that all the energy users types listed in the Table 4.4 are required for the achievement of the energy sufficiency status encompassing: grocery stores , small restaurants , entertainment activities , irrigation systems , workshops and the specific processing activity typical of the region being modelled. Note that processing activities subject to seasonality will only be considered for a four-month period.

4.5.12. Assembling archetypes for the construction of communities

After outlining the composition of the different energy sectors and their respective energy users, the next step is to create several plausible communities to be analysed using the proposed approach. The communities are constructed based on the following logic:

1. Three different regions are considered: lowlands, highlands and valleys.
2. For each region, five community sizes in terms of population (200, 500, 800, 1000, 1500) are defined. This range is included in the optimal household's range for the deployment of mini grid solutions as already explained [11].
3. For each community size, four different stage of development are considered varying the UBN level as explained in section 4.5.7 .The UBN levels chosen for the analysis are 96, 90, 70 and 56% that corresponds to the thresholds for each stage of development. To simplify the terminology during the analysis the four stages of development are going to be called generally archetype 1 , 2, 3 and 4.
4. For each UBN level considered, the reasonings and criteria explained before are followed for the structuring of the energy sectors. Thus, considering both the regional area and the community size as variables that influences the criteria used.

   In conclusion a total of sixty different archetype structures of rural communities are modelled (20 for each region).

4.5.13. Electric demand analysis

To evaluate the total electrical demand of each of the 60 archetypes, RAMP is used [45]. The model performs a bottom up process that takes the archetypes as input and computes the annual load curve for each day of the year, generating 365 stochastic daily profiles with a one-minute time resolution. By analysing the load curve data, it is possible to determine the minimum, average, and peak power requirements (kW), as well as the daily and annual electricity demand (MWh) for each community archetype. Moreover, these estimates are also calculated for each energy sector of every archetype individually, enabling to examine the specific energy requirements and consumption patterns for each sector within the community. This allows to determine the percentage contribution of each sector to the overall demand and examine their respective impacts for each archetype considered. The main results, analysed in Chapter 5, will be:

1. Yearly electrical consumption (MWh per year).

2. Peak power values. Peak power refers to the maximum amount of power required during a specific period when energy demand is at its highest. Understanding the peak power demand is a critical component of energy access projects, as it ensures that the energy system can be appropriately designed to meet the needs of the community or region it serves. The value of peak power is crucial in energy access projects because it determines the capacity and size of the energy system needed to meet the peak demand of a community.

3. Daily average load curves, especially useful in order to understand the distribution of the loads throughout the day for the whole community and for all the energy sectors considered.

4.6. Validation Process

After analyzing sixty different archetypes of communities in the highlands, lowlands, and valleys (as presented in Section 5.1), the research focus shifts towards validating the results obtained from modeling the residential sector's monthly electrical consumption. The residential sector is of extreme importance, as it contributes to more than 70 % of the total community electrical load.

The objective of the validation process is to confirm or adjust the previous modelling of the residential sector. To achieve this, real data of monthly electrical consumption from across the entire country will be analysed. The validation process will concentrate on the following key objectives:

1. Assessing the accuracy of the previously developed model in predicting the monthly electrical consumption of the residential sector. Thus, identifying any discrepancies or inconsistencies between the modelled and actual monthly electrical consumption data.

2. Understanding the crucial factors that contribute to energy consumption patterns by analysing a set of variables that may influence electricity consumption in the residential sector. Variables such as altitude, distance from the grid, poverty-related variables, and others are important factors that may influence monthly electricity consumption

values. The primary objective of this analysis is to understand the nature of the correlations between these variables and monthly electricity consumption values.

It is important to verify the existence and nature of such correlations, particularly with the main drivers used to build the archetypes, to confirm the relevance of the methodology used. In fact, if one of these main drivers does not have any significant correlation with electrical consumption, then it would be necessary to rethink the thought process used in creating the archetypes. By conducting this analysis, it is expected to identify the most influential variables that contribute to energy consumption in the residential sector and, possibly, further refine the archetype creation methodology.

Therefore, the achievement of both goals will allow the development of a more accurate and reliable modelling of the residential sector based on the insights gained from the validation process. Figure 4.6 proposes a summary of the procedure described in the following sections.

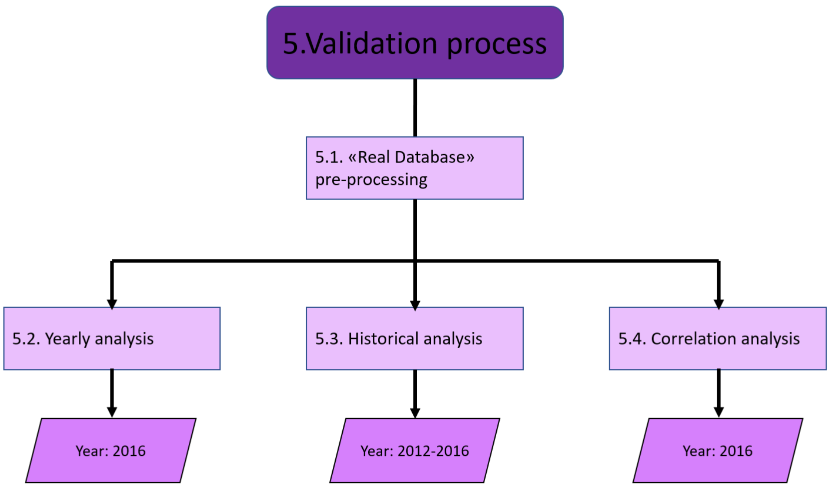


Figure 4.6: Flow diagram of the procedure.

It is essential to highlight the significance of the new large database made available by Andersen et al. [6] in the research project. The database contains comprehensive information collected between 2012 and 2016 in the nine departments of the country, encompassing different sectors such as residential, industry, mining, and others. This extensive availability of data represents a great opportunity, especially in developing countries, where insufficiency, low quality, and poor reliability of data are significant challenges, particularly in rural areas. In fact, the database includes valuable information related to household electricity consumption values, which is the critical data analysed in this part of the study.

The database used in the research project has been named the *"Database A"* to distinguish it from other databases used to complement and achieve the whole validation process. This database has played a crucial role in validating the results, providing comprehensive and accurate information that has allowed to refine the methodology.

4.6.1. Pre-processing and harmonization of data

Database A

Database A contains detailed information on the monthly electrical consumption for the residential sector of Bolivia. The data is organized based on the nine departments, and for each department, the database captures the monthly electrical consumption measurements for each household. Along with the measurement of electrical consumption, each household is identified by a unique municipal code that enables the acquisition of location-specific information. These characteristics allow for a minimum aggregation of data at a municipal level. The data is also temporally characterized, with each electrical consumption value representing a specific month and year in which the measurement was taken.

However, Database A is characterized by three relevant limitations that hinder a direct analysis of the monthly electrical consumption data:

1. Firstly, the database's structure permits the analysis of electrical consumption patterns with a minimum granularity that can capture municipal levels at most. This provides valuable insights into the energy consumption behaviour of households in Bolivia. However, this limited geographical resolution, hampers the identification of clusters of houses that could represent communities. As a result, a more detailed analysis at the community level was not possible.

2. Due to the same reason, thus limited geographical resolution, it is also impossible to determine if the monthly consumption measurements of the database are representative of rural or urban contexts.

3. Finally, to conduct a comprehensive analysis of electrical consumption behaviour, fundamental variables such as altitude or UBN levels associated with households must be considered. Unfortunately, Database A lacks further characterization by these variables.

To enhance the analysis of electrical consumption, overcoming limitations 2 and 3 is essential. Integrating additional databases that provide fundamental missing information for each measure of electrical consumption is crucial. Therefore, we propose utilizing two additional databases to fully exploit the potential of Database A.

Database B

Database B aims to address limitation number 3 by collecting missing information on crucial factors that may influence household electrical consumption. This database was constructed by combining data from three available databases, namely CNPV2012, Population Poverty2012, and OnSSet [14],[9]. The harmonization process involved several steps:

1. **Data checking**: involves checking the three databases for overlapping information and removing any duplicates or irrelevant values as part of the data cleaning process.

2. **Filtering for rural communities**: the data was filtered to focus the analysis on rural communities by imposing an electrification rate equal to zero. The electrification rate variable, which was already present in the databases and associated with each community, served as a means of identifying rural settlements. Only communities with an electrification rate of zero were included in the subsequent analysis.

3. **Selection of relevant attributes**: involves selecting a set of variables, or "attributes," from the three databases. These attributes are associated with each community and represented the missing variables from Database A. The creation of Database B was motivated by the need to find these missing variables, which are necessary for the subsequent analysis. Table 4.5 presents a list of the selected variables.

Attributes
Unsatisfied Basic Needs [UBN]
Altitude
Distance from the Power lines [Km]
Road Distance [hours]
Electrification Rate
Travel hours from the closest city

Table 4.5: List of Attributes selected for the composition of Database B.

4. **Merging all the information in a unique database**: involves the actual composition of Database B.

5. **Group all the communities by municipality**: The fifth step consists in organizing all the communities by their municipality of belonging.

After constructing Database B, the next step was to associate its attributes with Database A to overcome limitation number 3. However, this posed a challenge as data in Database A could be aggregated at the municipal level, while data in Database B was only available at the community level. Therefore, directly associating the attributes of Database B with the data of Database A was not possible.

To address this challenge, an additional step was necessary to integrate all the variables of Database B into Database A and associate them with monthly electrical consumption measurements of households. This involved computing a "municipal average" for each attribute, where a weighted average was computed between all the communities belonging to the same municipality. The weight was determined by the total number of inhabitants in each community.

It is important to note that this procedure represents a first approximation and may have significant consequences on subsequent analyses. For instance, households belonging to the same municipality are characterized with the same averaged attributes, even though there may be differences between communities within the same municipality in terms of attribute values. This means that the analysis loses the ability to represent a deeper level of resolution regarding individual communities' characteristics. Nonetheless, this approach was necessary to proceed with the analysis.

Database C

To overcome limitation number 2, the availability of Database C, created by the authors of [44], was fundamental. In fact, this database contains a list of all Bolivian municipalities from the 2012 Census, including a variable that express the urban rate of municipalities. This variable was critical in the filtering method that was employed to address limitation number 2. This method involved setting an urban rate constraint equal to zero, which led to the selection of only 160 "rural municipalities" out of the initial 338 that represent all Bolivian municipalities.

This approach enabled the identification of a list of all the municipal codes that represent rural municipalities. This list will be used to select only data, coming from Database A, that closely reflects rural contexts and thus rural households consumption values. It is important to note that this filtering method is a first approximation and may not capture all rural households' characteristics accurately. Nonetheless, it is a necessary step to proceed with the analysis and helps overcome the limitations posed by the available data.

Summary

Figure 4.7 summarizes the whole procedure undertaken.

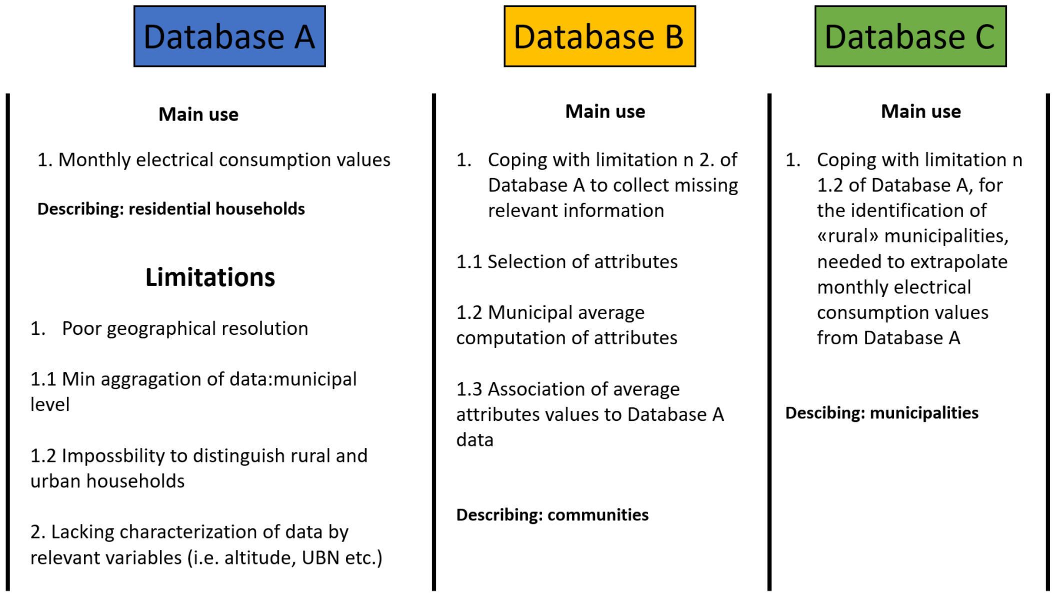


Figure 4.7: Summary: pre-processing procedure.

4.6.2. Electrical consumption analysis

Only after having solved the main limitation of Database A, the main focus of this chapter, the electrical consumption analysis, can be performed. However, before diving into the in-depth analysis, it is essential to extract accurate information from Database A. To collect the required data, the following steps need to be followed:

1. Filter the data to select only residential consumption data. In fact, the database contains information on four energy sectors: Residential, Public, Commercial, and Mining.

2. Select the time frame for the analysis: either a one-year or a multi-year analysis.

3. Filter the data to select only "rural" municipalities, obtain from Database C.

4. Filter the data to select only Highlands, Valleys or Lowlands electrical consumption values based on the the altitude variable, which was obtained from Database B. In this way it is possible to analyse each altitude range separately.

5. Clean the data by removing outliers using the Z-score method. Any data point with a Z-score greater than 3 is considered invalid and is discarded.

This enables to gain a better understanding of the three subsequent analyses that will be performed: yearly, historical and correlation analysis.

Yearly analysis

The analysis begins with an examination of monthly residential electricity consumption for the year 2016. This particular year was chosen because it represents the most recent data available within the time span of the database (2012-2016) and thus provides a better understanding of the current electricity consumption trends in rural municipalities. Additionally, as years progress, more data is collected in the database, increasing the quantity and improving the accuracy of future results. This increase in inputs and accuracy allows for more effective utilization of mathematical deductions and statistical methods.

For this initial analysis, special attention will be given to identifying seasonal trends in electricity consumption, with the aim of identifying which months exhibit significant deviations from the yearly average in electricity consumption.

Historical Analysis

The second analysis builds on the concepts explored in the first and extends the investigation to cover the entire time span between 2012 and 2016. The objective of this historical analysis is to identify any relevant trends in electricity consumption over time that could offer insights into the development trajectory of electricity access.

Correlation Analysis

The third analysis aims to assess the correlations between monthly electricity consumption and the attributes listed in Table 4.5. The objective is to identify the most influential variables on electricity consumption, using the 2016 data as a reference for the reasons previously explained.

Compared to previous analyses, the current one has one unique difference: it is conducted at the national level, which means that there is no further division of municipalities based on altitude. This choice aligns with the specific goal of the analysis, which aims to validate and enhance the methodology's archetypes creation procedure on a country-wide scale. Thus, a national-level analysis is appropriate and necessary for this purpose.

4.7. Rural demand estimation process improved

After completing the validation process, it has emerged the necessity to re-model the residential sector energy users due to significant discrepancies between the electrical consumption values of real measured data and the ones simulated through RAMP. The objective of this section is to improve the first methodology approach used for estimating the electrical demand of rural communities by incorporating the results obtained from the validation procedure. Subsequently, an electrical demand analysis will be conducted to compare the initial approach with the improved approach.

4.7.1. Remodelling of the residential sector

The re-modelling of the residential sector is based on the results of the validation procedure, specifically the Electrical consumption ranges (see 5.2.1). To improve the accuracy of the existing methodology, the following steps are taken:

1. Introducing a new residential energy user for each region is essential to improve the level of detail in the residential sector and represent the transition between the low-income (LI) and high-income (HI) households, which are characterized by a significant gap in electrical consumption. The MI household user is introduced to fill this gap and provide a more accurate representation of the residential sector. Additionally, the MI household represents the electrical consumption values identified by the 2nd ECR, making it a crucial addition to the methodology.

2. A new procedure is implemented to determine the proportion of households classified as HI, LI, and MI within the community. The poverty level reflected by the UBN is still used to approximate the percentage of LI households in the total population. However, the rest of the population is now divided into equal percentages between MI and HI households, except for the first archetype, which is still characterized by the absence of MI households, thus remaining the same as before. For example, if the UBN level is 70 %, it is assumed that 70 % of the households in that community have low electrical consumption, while the remaining 30 % is divided equally between HI and MI income households, each representing 15 %.

3. To ensure an accurate estimation of monthly electrical consumption values using RAMP, a simple calibration of the inputs is necessary to match the measured data of ECRs for each region. This involves varying the number of appliances, while keeping the same basket of appliances previously selected with the first methodology, until the estimated monthly electrical consumption values obtained through RAMP fell within the ranges identified.

   The presence or absence of refrigerators in the basket of electrical appliances is a crucial factor to consider during this step, as they have the highest impact on total electrical consumption. Therefore, to accurately match specific electrical consumption ranges for MI and HI households, it is necessary to consider a percentage of those categories without fridges. Hence, the main difference between MI and HI households is primarily based on the total percentage of each category that has a fridge. For instance, in the highlands only 25% of HI households has refrigeration, while the percentage is 10% for MI households.

4.7.2. Electrical demand analysis comparison

After re-modelling of the residential sector, the improved methodology follows the same process as described in subsection 4.5.13, starting with the evaluation of the electrical demand for typical rural community archetypes. As done previously, the model uses a bottom-up approach to calculate the daily load curve for each day of the year, resulting in 365 stochastic profiles with a one-minute time resolution. However, the contribution of the residential sector has changed, affecting the total load curve and peak power.

To assess the impact of these changes, the new results will be compared with the previous ones, highlighting the importance of the validation process. Overall, the analysis will build upon the previous work while accounting for the updated residential sector, enabling a more accurate understanding of the electrical demand for rural communities.

4.8. Hybrid micro-grids sizing: practical examples

Through the development and implementation of a novel methodology, a preliminary demand assessment of non-electrified rural communities has been conducted. This approach goes beyond the conventional conceptualization of demand in off-grid areas, which is often limited to the solely residential sector. Instead, it has been tailored to the specific needs and context of targeted communities, allowing for a thorough analysis of the electrical demands and the drivers that influence their variability.

To showcase the impact of this methodology on sizing mini-grid systems, three rural communities located in different contexts - highlands, lowlands, and valleys - have been selected as case studies. The purpose of these case studies is to underscore the significance of gaining a comprehensive understanding of the developmental needs of communities to support rural energy access projects and electrification strategies.

The case studies will be used to study several factors that affect the optimal sizing through the following analysis:

1. Firstly, the impact of altitude will be examined, with a focus on communities that have already achieved energy sufficiency (fourth archetype see 4.5.7). In this analysis, the

sizing process will be performed under the hypothesis that the three communities differ only in terms of their altitude characterization, while all the other drivers that influence the load remain constant. Therefore, by using the same level of UBN (Unsatisfied basic needs) and community size, the impact of altitude is isolated.

2. Additionally, the impact of remodelling the residential sector will be analysed. The sizing process will be performed considering the initial methodology implementation and then compared with the sizing results of the first analysis. As the remodelling is expected to have the most significant impact in the highland community, our comparison will be limited to this region.

3. Lastly, the first sizing results will be compared with another analysis that does not consider processing activities in the load curve. This comparison will help to understand the weight and influence of processing activities in the optimal configuration of the system. Also this analysis will discuss only the case of the highlands community.

These analysis will use two supporting tools: RAMP and MicroGridsPy, which have been previously discussed in sections 4.2 and 4.4. RAMP is a stochastic bottom-up tool ,used in the methodology implementation to simulate high temporal resolution load curves for rural communities archetypes. Meanwhile, MicrogridsPy is a bottom-up linear programming optimization model that can perform two-stage stochastic optimization to size mini-grids. Both tools will be employed to suit specific requirements of the different study cases, and RAMP's outputs will serve as inputs for MicrogridsPy for the load demand. In fact, the load demand is one of the main exogenous input parameters needed by this model together with the assessment of the renewable energy potential of the communities under study.

4.8.1. Communities' selection and renewable energy assessment

To conduct the sizing analysis, three rural communities located in different contexts - highlands, lowlands, and valleys - have been carefully selected as case studies. The selection process involved identifying rural areas that could serve as representative samples for each altitude range, with a specific focus on identifying communities that were well-suited for implementing the transformation activities outlined in the methodology (see 4.5.10).

In the end for the highlands the community of "Challa Arriba" was selected , for the lowlands the community of "Manuel Ascencio Padilla" and the community of "Tabacal" for the valleys. Therefore, knowing their coordinates it was possible to perform a renewable energy assessment, necessary as an input for MicrogridsPY for each of the locations, accomplished using the online platform https://www.renewables.ninja/. For each community, a solar hybrid mini grid system has been considered the best off-grid option. Hence, the online platform, considering solar irradiation and other specifics (i.e. tilt and azimuth angles), computes the output of a nominal unit of Photovoltaic Panel in the area per every hour of the year.

4.8.2. Methodology implementation: building load demand curves

To accurately determine the appropriate size and cost of the system, it is crucial to consider the load demand as a critical input factor. It is also essential to understand the characteristics of the simulated load curves that represent the electrical consumption of the selected communities under various conditions studied. Our methodology constructs different community archetypes that are used to create simulated load demand curves using RAMP. These curves serve as input for MicrogridsPY to optimize the sizing process. Table 4.6 provides a summary of the characteristics of the community archetypes used for the analysis.

Analysis	Load curve	UBN%	Altitude	Pop	Extra features
First analysis	1	56	Highlands	500	No extra features
	2	56	Lowlands	500	
	3	56	Valleys	500	
Second analysis	4	56	Highlands	500	No residential remodelling
	5	56	Lowlands	500	
	6	56	Valleys	500	
Third analysis	7	56	Highlands	500	No processing act.

Table 4.6: Characteristics of load curves used for the sizing process analyzes.

4.8.3. Optimal sizing: MicrogridsPY

After preparing the load curves and renewable energy assessment to use as inputs for the sizing model, it is necessary to establish fixed techno-economic parameters, as presented in Table 4.7. These parameters remain constant throughout all optimizations, as varying them falls outside the scope of this analysis.

Consequently, MicroGridsPy is employed using a Linear Programming (LP) optimization that provides the sizing of an isolated system able to satisfy at the minimum cost a given load demand. Indeed, the objective function of the model is set to minimize the Net Present Cost (NPC) of the system. Ultimately, Table 4.8 showcases the primary outputs of the sizing that will be discussed in Chapter 5 section 5.4.

Although the LP optimization framework adopted for this study does not allow for time-evolving constraints or the expansion of the system capacity in response to non-linearly time-evolving load demand, this limitation is not relevant for the study's purpose. In this regard, it is worth remembering that using an archetype approach provides a simplified

Description	Value	Unit
PV Output	Output of a nominal unit of Photovoltaic Panel in the area per every hour of the year	kWh x 8760
PV Investment Cost	1000	$/kW
Genset Investment Cost	2000	$/kW
PV O&M Cost	2% of Inv. Cost	$/ year
Genset O&M Cost	2% of Inv. Cost	$/ year
Cost of the Fuel	0.71	$/lt
Genset Efficiency	0.3	%
Battery Investment Cost	400	$/KW
Battery O&M Cost	2% of Inv. Cost	$/year
Battery Efficiency	0.96	%
Battery DoD	0.2	%
Discount Rate	0.1	%
Years of Operation	20	years

Table 4.7: Main MicrogridsPY techno-economic parameters.

Dimension	Description	Unit
Component's Size	Optimal size of : PV modules, Genset and battery pack	kW and KWh
Energy Flows	Optimal energy flow from and to each technology installed every hour of the year	kWh x 8760
NPC	Net Present Cost	$
LCOE	Levelized Cost of Electricity	$/KWh

Table 4.8: Main MicrogridsPY outputs.

method for quick and easy first-round estimates and serves as an alternative to more complex and often less accurate estimation techniques. Therefore, the load demand of a typical year of consumption in the study area is repeated identically for every year of the project lifetime without compromising the validity of the results. In fact, the analysis's focus is to compare different energy systems from an overall perspective and capture how the primary drivers that influence demand characterization impact the sizing and cost of hybrid microgrid systems.

On the other hand, the techno-economic outputs of MicrogridsPY are intended to be used to quickly identify priority strategies at the national level but without aiming to accurately reproduce the physical behaviour of all modelled technologies. For instance, this results could support a rapid identification of the most suitable locations, where more detailed and thorough assessments can start, improving the accuracy and efficiency of electrification planning. In this case, more complex optimization frameworks could be implemented to obtain higher level of techno-economic detail.

5 | Results and Discussion

5.1. First methodology rural demand estimation results

This section presents and discusses the main findings from the electrical demand analysis of the archetypes discussed in section 4.5. The next sections are organized as follows:

1. Firstly, RAMP results, regarding the total load of the communities archetypes, are presented. Hence, this analysis shows the general macro behaviour of the yearly electrical consumption across highlands (HL), valleys (VA), and lowlands (LL).

2. Next, the analysis shifts its focus to the energy sectors and their contribution to the overall demand for electricity. The results explore the specific details that make up and influence the overall macro behavior previously mentioned. The objective is to gain a more comprehensive understanding of the primary drivers behind the total load and their impact on electricity consumption.

5.1.1. Total electrical demand results: community level

Results at the community level are shown in Figure 5.1, where the yearly electricity consumption values are presented across the four stages of development for each region and for selected community sizes of 1000 and 500 inhabitants. These graphs provide a good starting point for observing general behaviours influenced by the three main drivers: UBN (Unsatisfied Basic Needs), altitude and community size. Further examination of each energy sector individually will help in understanding their influence on the total load. Although detailed analysis of each energy sector is forthcoming, some initial observations can be made based on these graphs:

1. **Stages of development: UBN's influence on the demand.** An examination of the evolution of each targeted community within its four archetypes (as UBN gradually decreases) reveals a general progressive increase in the total demand. This demand increasing behaviour exhibits a repetitive pattern regardless of community size. This is why the analysis considered two communities of vastly different sizes. Specifically, the

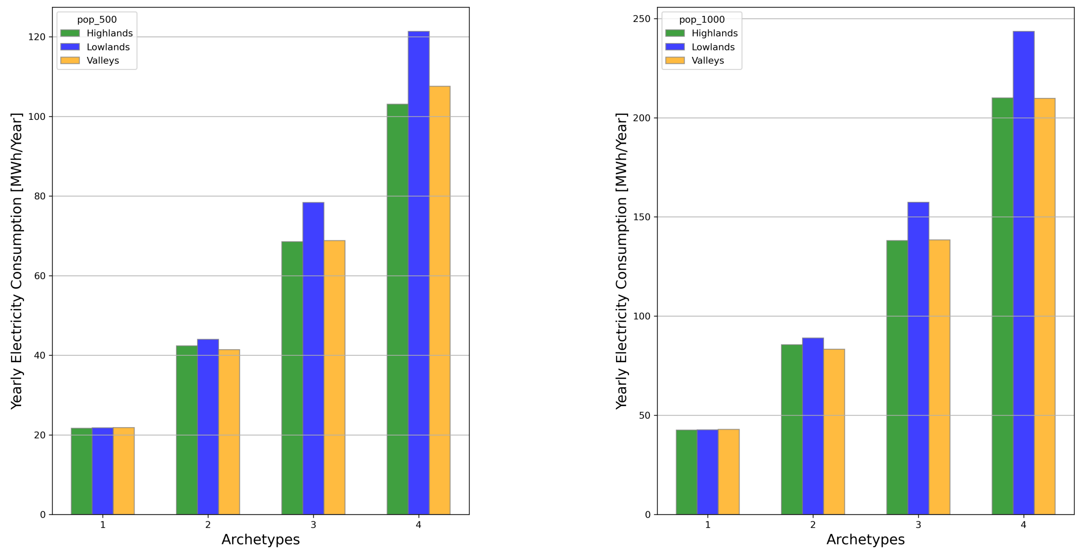


Figure 5.1: Yearly electrical consumption comparison between regions: 500 and 1000 inhabitants communities.

transition from the first archetype to the last one, which represents the achievement of energy sufficiency, results in a more than five-fold increase in total electrical consumption compared to its initial value for all three regions. This behaviour can be attributed to two main factors:

(a) An increase in high-income households and a corresponding decrease in low-income households.

(b) Improvements in the community structure that develops new energy users and types across the energy sectors, following the methodology described in Chapter 4.

2. **Altitude: electrical demand comparison between different regions.** Comparing regional electrical consumption values for each stage of development reveals some noteworthy observations:

   (a) For the first archetype, regional differences are virtually non-existent since the differences in modelling the residential sector, the only energy sector present in the community, do not manifest.

   (b) Regional differences start to manifest from the second archetype to the last one, with the lowland's region exhibiting always the highest electrical consumption.

On the other hand, differences between the electrical consumption of the highlands and valleys are almost negligible.

The reasons behind the above-mentioned behaviours are going to be better interpreted in detail later on when the analysis of energy sectors will start.

5.1.2. Residential sector results

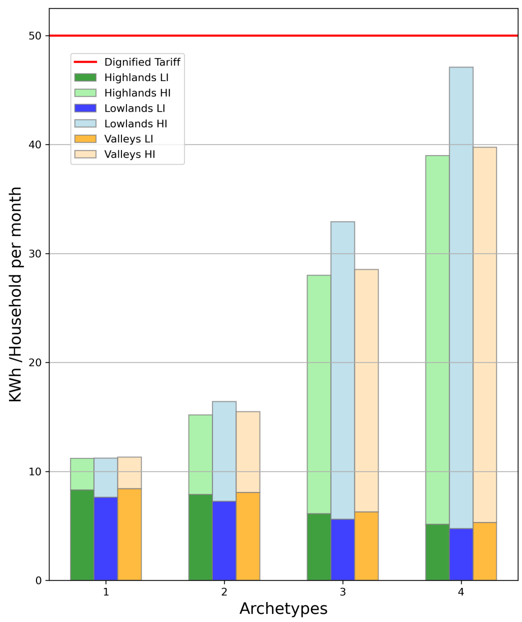


Figure 5.2: Monthly electrical consumption comparison between regions and per income classes.

Figure 5.2 provides an analysis of monthly electrical consumption per household for all regions and across the four archetypes, including a breakdown of the percentage contributions of high-income (HI) and low-income (LI) households to the residential load. The provided procedure outlines the steps taken to calculate these percentage contributions for each region and archetype:

1. A 30-day simulation is performed using RAMP with only one residential energy user at a time. This results in finding the monthly electrical consumption of one single HI and LI households individually.
2. Choosing a fixed number of households, to represent the community.

3. Calculate the total number of HI and LI households based on the percentage of UBN of the archetype considered. For instance, if we are analysing the third archetype (70% of UBN) then the total number of LI households is the 70% of the total households.
4. Compute the total monthly electrical consumption for each residential user type by multiplying the monthly consumption obtained in step 1 by the number of households calculated in step 3
5. Calculate the percentage contribution of each residential user type to the total residential sector by dividing their total monthly consumption (calculated in step 4) by the combined consumption of HI and LI households that represents the total consumption of the residential sector.

In the end, the values displayed in the figure represent the average monthly consumption between high-income (HI) and low-income (LI) households, which changes across the archetypes due to the variations in their percentage contributions. Thus, the analysis represents a generic "average" household, providing an overview of the residential sector's situation as a whole.

The results are measured for one month, enabling clear comparison with the Dignified Tariff, represented by the red line in the graph. The Dignified Tariff is the threshold that must be met to achieve the energy sufficiency status for the residential sector. Therefore, these observations can be drawn from Figure 5.2:

1. **Stages of development: UBN's influence on the demand.** As the UBN percentage decreases across the four archetypes, the residential sector's electrical consumption increases significantly. In fact, the electrical consumption in the fourth archetype is almost four times higher than in the first one. The decrease in UBN, which determines the distribution of percentages devoted to high-income (HI) and low-income (LI) households, is directly linked to this increase. High-income households, which have more electrical appliances and consume more electricity, make up a larger proportion of the population as the UBN level decreases. These households have a total electrical load more than five times higher than low-income households, with fridges being the most energy-intensive appliance. In fact, over 50 % of high-income households' electricity consumption comes from fridges. Therefore, when modelling the residential sector's electrical demand, the presence of fridges in high-income households is the most important factor to consider.
2. **Altitude: electrical demand comparison between different regions.**
   (a) For the first archetype, regional differences are virtually non-existent since the differences in modelling the residential sector, the only energy sector present in

the community, do not manifest. This is because low-income households (which constitute 96 % of the community) have similar appliance ownership and activity patterns, which result in low consumption and negligible regional differences.

(b) Regional differences in electrical consumption start to manifest from the second archetype to the last one, with the lowland region consistently exhibiting the highest consumption. In contrast, the highlands and valleys show only slight differences between them. These variations primarily reflect how climate differences have been modelled in RAMP being aware that fridges, that are the most energy intensive appliance, are highly sensitive to ambient temperature. Modular duty cycles are employed to better reproduce the actual behaviour of fridges with respect to the identified average temperature assumed for each region. Indeed, the modelling of fridge duty cycles, which is influenced by temperature, is one of the main cause that lead to variations in electrical consumption across different regions. As a result, the lowlands, with its high temperatures, exhibit the highest electrical consumption. On the other hand, the valleys have lower electrical consumption, as their average temperature is lower than the lowlands, but still higher than in the highlands, which has the lowest average temperature of all the regions considered. Appendix A provides additional comprehensive information on the modelling of fridges' duty cycles. Moreover, Table 5.1 compares the relevance of fridge consumption with the consumption of high-income (HI) and low-income (LI) households for each region.

Monthly Consumption [KWh]	Lowlands	Highlands	Valleys
LI	7,68	8,31	8,36
HI	88,32	68,915	73,61
Fridge	71,29	58,12	63,4

Table 5.1: Monthly electrical consumption comparison between regions.

3. **Energy sufficiency status and the Dignified Tariff.** A separate discussion about the status of energy sufficiency and its achievement is necessary. The Dignified Tariff serves as a benchmark for meeting the energy sufficiency standards as outlined in Chapter 4, subsection 4.5.11. However, it is worth noting that no residential sector has met this threshold. While in the lowland's region, electrical consumption is close to the benchmark at just over 47 kWh per month, both the highlands and valleys fall short with an average consumption of less than 40 kWh per month. However, the results presented only offer a partial glimpse of the residential sector. In fact, there are significant disparities in electricity usage between the two types of households mod-

elled. As such, the HI households, which tend to have much higher electricity consumption rates, are able to achieve the energy sufficiency threshold in each region, while the LI households do not, as illustrated in Table 5.1. Therefore, this analysis provides insight into a residential sector where the average consumption between HI and LI households never reaches sufficiency, even if the percentage of HI households far exceeds the sufficiency threshold.

Furthermore, while the same basic needs of households are met across different regions, the strong dependence of refrigeration on temperature leads to a significant increase in overall electricity consumption. However, this increase is not necessarily indicative of improved living conditions. Therefore, it might be beneficial to adjust the sufficiency thresholds to account for climate variations in rural areas. This suggests that using nationwide standards, based only on electrical consumption, for an entire country may not always be the best practice, especially given the presence of strong regional differences.

These findings provide a foundation for future research to explore and further understand the complexities of energy sufficiency and its implications for households in different contexts, particularly concerning energy-intensive electrical devices that significantly impact the electrical load.

5.1.3. Energy sectors break down

Figure 5.3 provides an analysis of the energy sector contributions breakdown for a highlands community comprising 500 residents, across the four archetypes. The figure comprises two graphs: one on the left shows yearly electricity consumption, while the other on the right shows peak power.

Yearly electricity consumption graph

1. **Residential sector**. As expected, the residential sector is the largest consumer of electricity in the community, accounting for over 70 % of the total energy demand across all four archetypes. This sector's percentage contribution to the overall electrical demand fluctuates due to: changes in the number of high-income households and due to the introduction of other energy sectors and user types. For instance, if the introduction of other users, such as IGAs users, is not significant enough to compensate for the increase in high-income households, the residential sector's percentage contribution will rise.

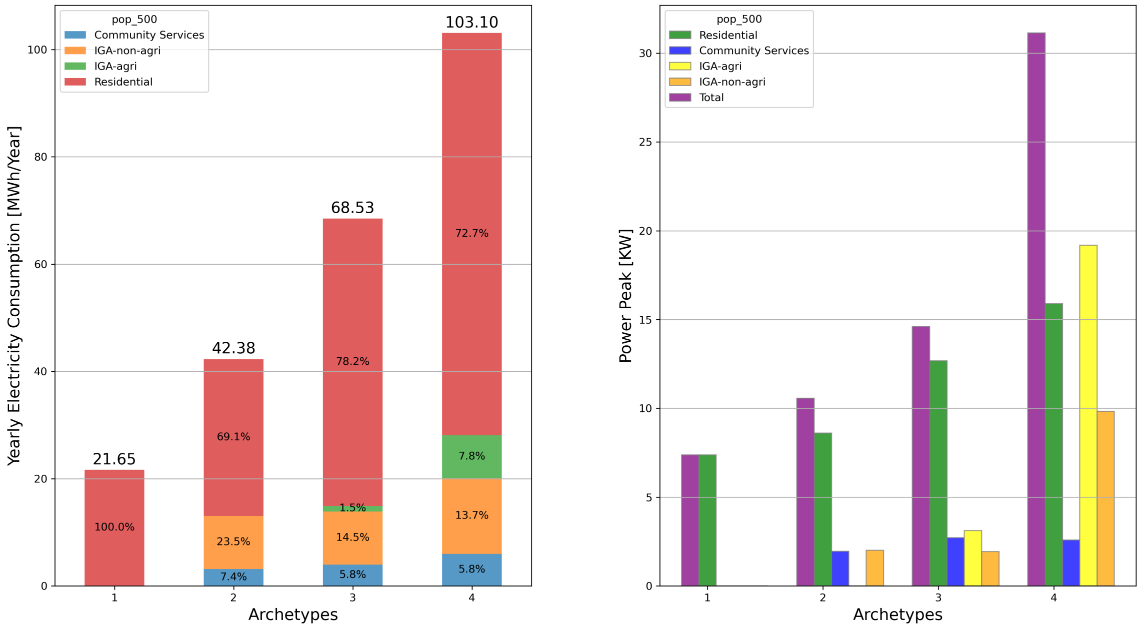


Figure 5.3: Highland community of 500 inhabitants : on the left the yearly electrical consumption break down per sector , on the right the peak power values .

2. **Community services**. Throughout all four archetypes, the contribution of community services to the total energy demand is always the lowest among all energy sectors, accounting for less than 10 %. Although the contribution of community services to the overall energy demand is relatively small, this sector plays a crucial role in providing essential energy services as described in 4.5.9 .

3. **IGA sector**. The IGA sector's total contribution to the overall energy demand can exceed 20 %, highlighting its significance in the community's energy needs landscape. The fourth archetype has the largest share, primarily due to the incorporation of processing activities in the agricultural IGAs sector.

Peak power graph

Peak power refers to the maximum amount of power required during a specific period when energy demand is at its highest. Understanding the peak power demand is a critical component of energy access projects, as it ensures that the energy system can be appropriately designed to meet the needs of the community it serves.

Across the first three archetypes, the residential sector consistently exhibits the highest peak power, which more than doubles as the community transitions from the first to the last archetype. Until the third archetype, the residential sector's peak power remains more than double that of the other sectors, making it the most significant contributor to the total peak power of the community. But, once the community has achieved energy sufficiency, the IGA sector's peak power surpasses that of the residential sector, primarily due to the introduction of processing activities that use equipment with high nominal power. As a result, the peak power of the IGA-agricultural sector reaches a value slightly lower than 20 KW that exponentially increases the importance of IGAs in the community's energy landscape. For this reason, the transition from the third to the fourth archetype results in the largest increase in the community's total peak power. In fact, the peak demand for the IGA sector's processing activities occurs during the same time windows as other sectors, significantly increasing the community's overall peak power. As depicted in Figure 5.8, the daily average curves of all three energy sectors for the fourth archetype exhibit overlapping peak demand times, which contributes to the significant increase in the community's total peak power.

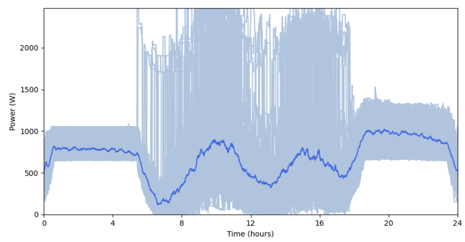


Figure 5.4: Community services.

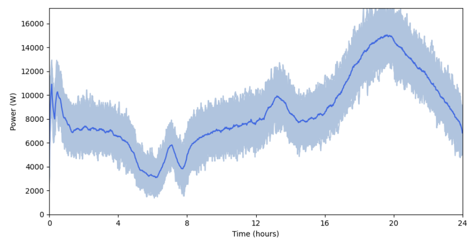


Figure 5.5: Residential.

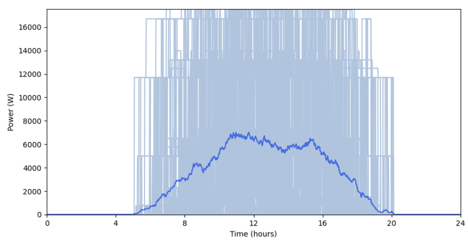


Figure 5.6: IGAs processing.

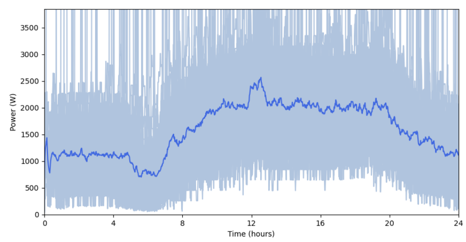


Figure 5.7: IGAs non-agri.

Figure 5.8: Daily load curves break down per energy sector: fourth archetype.

Community size influence

While the analysis presented in this section focuses on a specific community size and region, the observed patterns are consistent across different communities and regions. Thus, the findings can be considered representative of a general behaviour, with only minor adjustments and slight variations that reflect trends and observation already discussed. As evidence of this concept, Figure 5.9 presents the analysis results for a lowland community with a population of 1000, which differs from the previous analysis in terms of region and community size considered. Despite potential variations such as differences in fridge functioning and community size, the same observations confirm the general behaviour seen in the previous analysis, even though with higher overall values compared to the highland.

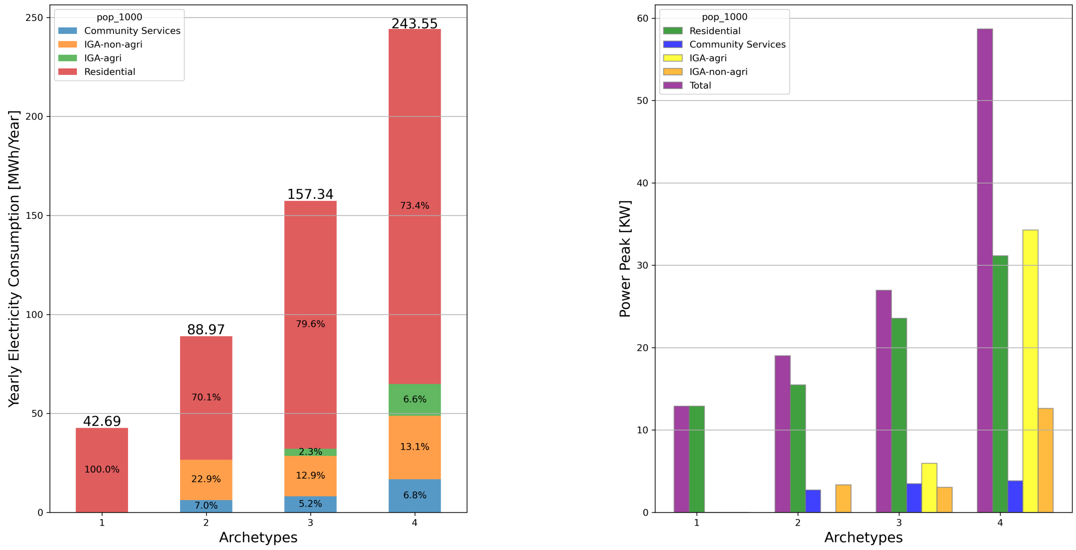


Figure 5.9: Lowland community of 1000 inhabitants : on the left the yearly electrical consumption break down per sector, on the right the peak power values.

5.1.4. Main conclusions first approach

The main conclusions derived from the analysis of these sections are the following:

1. Improvements in people's quality of life, achieved through access to electricity that satisfies their energy needs, can significantly increase electricity consumption, particularly when energy sufficiency is achieved.

2. Altitude, UBN, and community size, as well as communities' composition, proved to be crucial factors that influenced the electrical demand curve.

3. The residential sector is the largest contributor to the total peak power and electrical consumption of the community, making it a crucial factor in energy access projects.

4. The IGA sector plays a critical role in energy access projects, ensuring that community's energy needs are met comprehensively. Neglecting this sector can result in sig-

nificant energy deficits, hindering the community's economic growth and development. The results showed are significant, as they demonstrate the need for policymakers and energy planners to consider the IGA sector's electrical demand, especially due to the high peak power values of processing activities.

5. Failing to account for heterogeneity within a country could result in inaccurate predictions of electricity demand. Furthermore, the adoption of energy-intensive appliances plays a vital role in the variability of electrical demand. For instance, the acquisition of a refrigerator by a specific residential user type in a particular area can have a significant impact on the electricity required to meet their basic needs. The same reasoning can be applied to energy-intensive machinery dedicated to processing activities. As a result, it's essential to comprehend how various contexts can affect the penetration and consumption of such appliances.

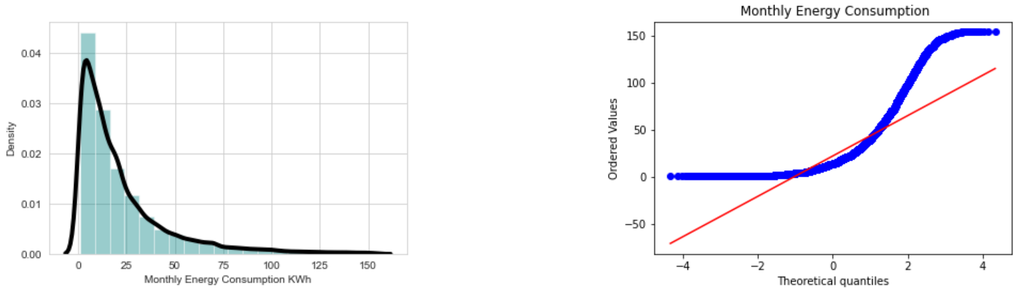
5.2. Validation Results

This section presents the results obtained from the validation procedure described in chapter 4, section 4.6. The results are divided into three parts: yearly analysis results, historical analysis results, and correlation analysis results.

5.2.1. Yearly analysis results

This section evaluates the 2016 residential electricity consumption analysis by dividing the results into three categories: highlands, valleys, and lowlands. For each region, a statistical analysis is conducted on the monthly electrical consumption measurements of all households in rural municipalities within that region. The statistical analysis includes measures of: the count of inputs (total number of households with a measurement in the region under study), mean consumption, standard deviation of the consumption data, minimum and maximum consumption values, 25th, 50th, and 75th percentiles of the consumption data, and frequency distribution of the consumption data.

The frequency distribution of the data was subjected to a Gaussian data test distribution analysis, which revealed that the distribution does not meet the criteria to be considered a Gaussian curve for all regions. Figure 5.15 displays the tests conducted for the highlands, but similar behavior was observed for both lowlands and valleys. Therefore, the mean value may not provide an accurate representation of households' electricity consumption. Instead, it is advisable to use the median value to obtain a general understanding of the typical monthly electricity consumption. Additionally, percentile values will play a crucial role in interpreting the data.



(a) (b)

Figure 5.10: Highlands data distribution on the left. Gaussian test on highlands monthly electrical consumption data on the right.

Therefore, the statistical analysis results, measured for each month, are used to identify three main Electricity Consumption Ranges (**ECR**), which have been defined as follows:

1. **First Electricity Consumption Range**: This range includes monthly electricity values from zero up to the 25th percentile, which represents the upper threshold of this range. This consumption behavior is typically associated with low-income households.

2. **Second Electricity Consumption Range**: This range encompasses monthly electricity values from the 25th to the 50th percentile. This consumption behavior is associated with households in transition between low-income and high-income. Therefore, it has been decided to introduce a new user type for middle-income households that will be considered for the future re-modelling of residential sector.

3. **Third Electricity Consumption Range**: This range comprises monthly electricity values from the 50th to the 75th percentile. This consumption behavior is associated with high-income households.

Figure 5.14 displays the ECRs for each month and zone analyzed. The absolute values of ECRs vary significantly among the regions, underscoring the importance of considering altitude as a driver of electrical consumption variation. Households located in the lowlands have the highest electricity consumption, particularly for the 3rd ECR's values, followed by those in the valleys and the highlands.

The graphs show that ECR thickness follows a consistent trend, progressively increasing from the lowest (1st ECR) to the highest (3rd ECR). This pattern is also reflected in the standard deviation values, which increase exponentially from the first to the third consumption range. This behavior highlights how the larger consumption range of high-income households compared to low-income households contributes to the increase in variability in electricity consumption. One possible interpretation of the results is that for high-income households, the burden of electricity bills has less impact on their activity patterns and usage of electrical appliances, not to mention their greater number of electric devices.

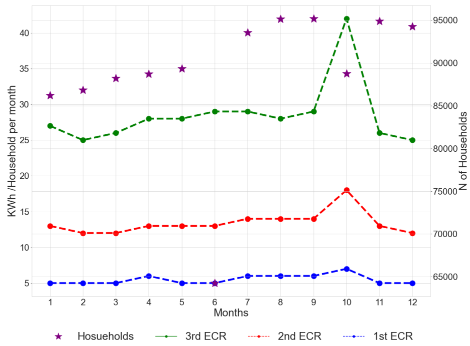


Figure 5.11: Highlands ECRs trend.

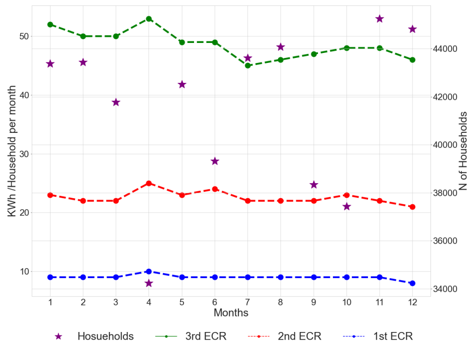


Figure 5.12: Valleys ECRs trend.

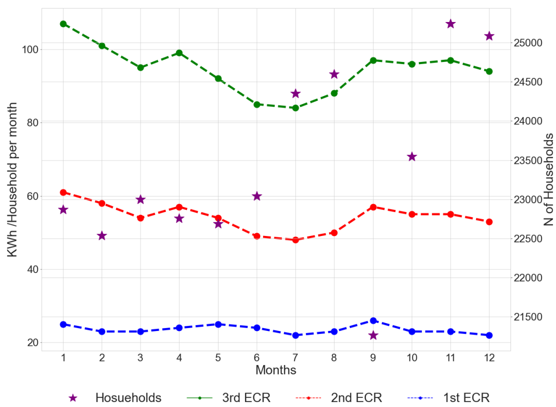


Figure 5.13: Lowlands ECRs trend.

Figure 5.14: ECRs yearly variations for all regions.

It is worth noting that the count of households' electricity consumption values is not consistent across all the months, and there is a substantial difference in absolute values between each zone. This behavior may be due to a lack of homogeneity in data collection and could affect the accuracy of the results proportionally to the count of data points.

Moreover, it's important to note that the analysis excluded values beyond the 75th percentile up to the maximum due to an exponential increase in the standard deviation. This increase led to a significant rise in the range of consumption variation and was associated with a sharp rise in absolute electrical usage. As a result, it was challenging to realistically model high-income households that could reach these exceptionally high levels of electrical consumption with extreme variability. Our conclusions are supported by the data and knowledge gathered throughout the methodology creation process and the electrical demand analysis results. In fact, these values may not be representative of households in a rural context, where high levels of electricity consumption are less common. Therefore, we concluded that the values of the last percentile could be interpreted in two ways:

1. **Mistakes in the filtering data procedure.** The data available had limitations in geographical resolution, so approximations were made to analyse rural electricity consumption. The filtering approach considered only rural municipalities with an urban rate of zero. it's possible that there were outliers within rural municipalities due to the presence of not only rural communities but also urban areas. Indeed, urban households tend to consume more electricity, as they are characterized by lower values of poverty rate and other crucial factors such as market availability.

2. **Home-based businesses.** In rural areas of developing countries, some households classified as residential households may run home-based businesses, resulting in higher levels of electricity consumption than those of typical households. Such households should be considered as Income Generating Activities (IGAs) instead of residential households. This phenomenon may contribute to the observed variability in electricity consumption.

Most representative ECRs

To gain an overview of residential electrical consumption, it is possible to calculate ECRs (Electricity Consumption Ranges)representative of a general behavior over the course of a year. This is achieved by computing the median of all percentile threshold values for each month for each ECR. By identifying the most representative ECRs, as showed in Table 5.2, it is possible to use them to characterize the electrical consumption patterns of low, middle, and high-income households in all three regions under consideration.

ECR [KWh/month]	Highlands	Lowlands	Valleys
1st	0-5	0-23	0-9
2nd	5-13	23-54	9-22
3rd	13-28	54-95	22-48

Table 5.2: Yearly electricity consumption ranges.

Table 5.2 highlights the significant regional disparities in electricity consumption. The harsh living conditions in the highlands result in the lowest consumption rates. Conversely, the valleys have much higher electricity usage than the highlands, typically consuming twice as much across all ECRs. However, it is in the lowlands that the most substantial impact on overall electricity consumption is present, with values almost twice as high as those of the valleys.

These findings emphasize the importance of considering the unique characteristics of different regions when modeling electricity usage in rural communities. By doing so, it is possible to better account for the diverse needs and behaviors of households across the country. Therefore, these results ,if rapidly compared with the ones obtained with the RAMP simulation (subsection 5.1.2), demonstrate even stronger disparities between regions of the ones that have been previously modelled. Hence, in order to improve the accuracy of the previously developed modelling methodology in predicting monthly electrical consumption of the residential sector, a remodelling will be necessary.

Seasonal Trends

To investigate whether seasonal trends exist in the electricity consumption of the residential sector, it is essential to study how electricity consumption ranges (ECRs) vary throughout the year. Seasonal changes, such as temperature fluctuations or different activity patterns, can affect households' electrical consumption and, in turn, expand or skew ECRs. Analyzing how the thresholds of each ECR change over the months can provide insights into seasonal trends. However, no seasonal trends have been found. This outcome could be attributed to the fact that in countries like Bolivia, which are situated near the equator, the distinction between seasons is less distinct. In depth details regarding the analysis performed are given in the Annex A.

5.2.2. Historical analysis results

To observe historical changes in electric consumption from 2012 to 2016, the same procedure as before (refer to 5.2.1) has been employed. The resulting most representative ECRs' thresholds are presented in Table 5.3 for each region.

Thus, the following observations can be drawn:

Highlands: The first and second ECRs showed no significant changes over the years, while the third ECR showed a slight increase of 2 KWh towards the end of the time span considered.

Lowlands: All three ECRs showed a continuous increase in electric consumption over time,

ZONE	ECR	2012	2013	2014	2015	2016
HIGHLANDS	1st	7	5.5	6	5	5
	2nd	14	13	13	13	13
	3rd	25.5	24	25.75	27	28
LOWLANDS	1st	19	21	22	24	23
	2nd	47.5	48	51.5	54.5	54.5
	3rd	88	85	92	95.5	95.5
VALLEYS	1st	7	7	8	10	9
	2nd	19	20.5	21	24	22
	3rd	43	45	46.25	50	48.5

Table 5.3: Yearly ECR thresholds evolution over time.

with a non-negative growth rate. Furthermore, the final increase in consumption from the first ECR to the third ECR increased from 4 KWh to 7.5 KWh.

Valleys: All three ECRs showed a continuous increase in electric consumption over time with a positive growth rate until the year 2015. Additionally, the final increase in consumption from the first ECR to the second ECR increased from 3 KWh to 5.5 KWh.

In conclusion, the results reveal that high-income households, represented by the third ECR, have exhibited the highest growth in electric consumption over the five-year period studied. Moreover, the lowlands region has shown the most significant improvements in terms of the absolute values of electric consumption across all three ECRs. Following the lowlands, the valleys and the highlands regions showed lower but still positive growth rates in their electric consumption.

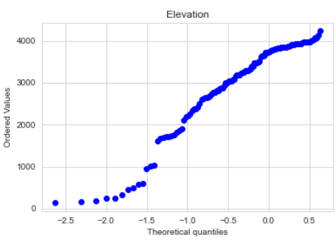
The observed trends may be interpreted as a reflection of the challenges involved in expanding electricity access in high-altitude regions. These areas may be less economically viable and offer fewer investment opportunities than other regions, and they may also lack existing infrastructure, making electrification more difficult. Despite varying rates of growth in electricity consumption across different regions, the overall increase in consumption suggests that rural electrification has improved. Furthermore, as mentioned earlier, the total number of measurements tends to increase over time further supporting the improvement in access to electricity. In fact, as detailed in Chapter 3, section 3.8.3, the government's recent efforts to improve rural electrification in Bolivia have been successful.

5.2.3. Correlation analysis results

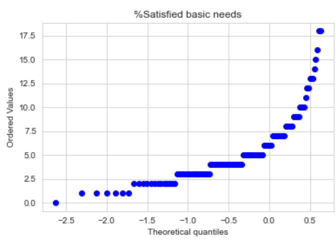
To better understand the relationship between the selected variables (see Table 4.5) and monthly electricity consumption at a municipal level, the primary objective of this analysis is to identify and quantify their correlation.

Correlation is a statistical relationship between two variables that can be positive, negative, or neutral, depending on the direction of their change. Among the different statistical methods available, this analysis has decided to use a correlation score approach, which is a statistical measure that indicates how closely two variables are related to each other. To calculate the appropriate correlation score, it is necessary to test the data set to determine if the variables' distribution is Gaussian. In fact, based on the distribution and characteristics of the data, different correlation scores may be better suited for the job.

In this analysis, a Q-Q test plot is used to test the main variables selected. The Q-Q test helps to determine if a data set is normally distributed or not. The results of the test indicate a non-Gaussian distribution for the variables under study. Figure 5.15 shows some examples of the Q-Q test performed on the variables.



(a)



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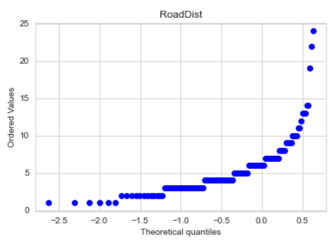

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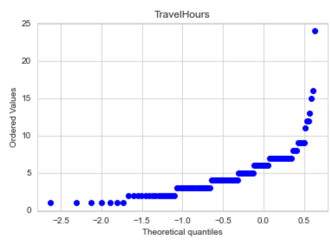


(d)

Figure 5.15: Distribution test examples.

After considering the distribution of the variables and the potential for a nonlinear relationship, the Spearman's correlation method was chosen. The Spearman's correlation coefficient is used to summarize the strength between two data samples: one represented by the variable being investigated and the other by the monthly electricity consumption value. This method is particularly useful when the variables have a non-Gaussian distribution and when it is not possible to know beforehand if the future relationships are characterized by a linear behavior. The Spearman's correlation test can also be used if there is a linear relationship between the variables, but it may have slightly less power than other correlation tests (e.g., may result in lower coefficient scores).

The correlation score is represented by a coefficient between -1 and +1, which represents the limits of correlation from a full negative correlation to a full positive correlation. The value of the coefficient must be interpreted, where often a value below -0.5 or above 0.5 indicates a notable correlation, whereas below those values suggests a less notable correlation. Hence, the selected Spearman's correlation method is applied to each month of the year 2016, showing the following trends:

1. The altitude variable has the highest absolute coefficient value, reflecting the strongest influence on electricity consumption. It is characterized by a negative correlation score that varies from -0.6 to -0.76.

2. The percentage of UBN has the second highest absolute coefficient value, characterized by a negative correlation score that varies from -0.3 to -0.5.

3. For all the other variables, it is not possible to observe a consistent behavior across the year, and the absolute values of the correlation coefficients never reach higher values than 0.35. Therefore, it is not possible to consider the existence of any meaningful correlation for these variables.

Table 5.4 shows an example of the correlation scores for the month of July. While Figure 5.16 shows a scatter plot example in which is possible to observe the behaviour already explained with the Spearman's coefficients.

	Spearman Score
UBN	-0.50
Elevation	-0.76
Road Distance	0.04
Number of Electrified Households	0.19
Travel Hours	-0.11
Distance_MV 2012	0.29
Substation Distance	0.13

Table 5.4: Correlation scores: month of July.

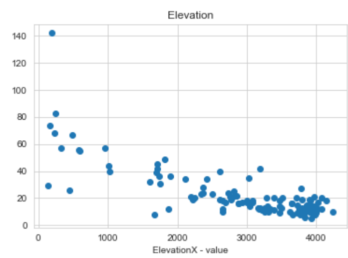


Figure 5.16: Scatter plots example.

The findings confirm the significant impact of altitude and UBN on residential electricity consumption and, consequently, on the archetype creation process described in Chapter

4. Specifically, altitude is found to be the primary driver of monthly household electricity consumption, with a negative correlation indicating that communities at higher elevations tend to have lower electricity consumption. Similarly, UBN also shows a negative correlation, although with a lower intensity.

Finally, the analysis did not find any significant correlations between variables related to community size, such as population, density, or the total number of electrified households. While this aligns with our archetype construction process for the residential sector, it is important to exercise caution when interpreting these results due to the approximations made during the pre-processing procedure. The absence of even a slight dependency is somewhat surprising, and it is possible that future studies with more accurate data and analysis methods could yield different results. Nonetheless, the importance of community size in shaping community structures should not be overlooked since, under our assumptions, it influences the type and number of community services and IGAs.

Additionally, despite searching for other influential variables that could have refined the archetype creation methodology, no such variables were identified beyond altitude and UBN.

5.2.4. Main conclusions validation process

The analysis of the previous results leads to the following main conclusions:

1. The altitude is the primary driver that influences monthly electrical consumption values of residential sector, followed by UBN. Hence, It has been proved the crucial role and relevance of such drivers in the archetype construction process described in Chapter 4.

2. Real monthly electrical consumption data showed significant discrepancies when compared to the modelled results, analysed in subsection 5.1.2, highlighting the need for a more precise and improved modelling approach that is capable of better capturing differences of communities with different altitude characterization.

3. Once again, it has been proven that failing to account for heterogeneity within a country could result in inaccurate predictions of electricity demand.

5.3. Improved methodology's results

This section presents and discusses the main findings from the electrical demand analysis of the archetypes described in section 4.7.2, as well as a comparison with the previous results. Hence, the structure follows the same logic as described in section 5.1. Accordingly, the next sections are organized as follows:

1. Re-modelling of the residential sector.

2. Analysis and comparison of the residential sector.

3. Breakdown of energy sector contributions and comparison.

By following this structure, the aim is to provide a clear and comprehensive understanding of the updated electrical demand analysis and its impact on the overall results. In addition, often the results are presented alongside the old methodology's results to enable a clear comparison between the two. In this way, the impact of the validation procedure's improvements is better highlighted.

5.3.1. Re-modelling the residential sector

The RAMP inputs for the residential sector have been calibrated to match the measured data of ECRs for each region. Figure 5.17 depicts the final configuration resulting from this procedure, which includes a new list of appliances and different percentages reflecting the presence of refrigeration for each residential segment. As a result, the monthly consumption levels for each residential user have been influenced by these new features.

	High Lands				Low Lands				Valleys				
Appliances	LI	MI	HI		LI	MI		HI	LI	MI		HI	
Indoor Light	3	4	4	4	3	4	4	4	3	4	4	4	4
Outdoor Light	0	2	2	2	1	2	2	2	1	2	1	2	1
Televsion	1	1	1	1	1	2	1	2	1	1	1	1	1
Radio	1	1	1	1	0	1	1	1	1	1	1	1	1
Phone Charger	2	4	4	4	2	4	4	4	2	4	4	4	4
Antenna	0	0	0	0	1	1	1	1	0	1	1	1	1
Freezer	0	1	1	75% without fridge	0	1	75% without fridge	1	0	1	85% without fridge	1	50% without fridge
Laptop	0	1	1	0	0	1	1	1	0	1	1	1	1
Mixer	0	1	1	1	0	1	1	1	0	1	1	1	1
DVD	0	0	0	0	0	1	1	1	0	1	1	1	1
Fan	0	0	0	0	0	2	1	2	0	0	0	0	0
Total number of appliances	4	8	8	6	5	11	10	11	5	10	9	10	9
Montlhy Electrical Consumption [KWh]	4,7	10	25		7.5	33		87	7	22		44	

Figure 5.17: Final configuration of residential RAMP inputs.

Overall, re-modelling the residential sector has led to a substantial reduction in electrical consumption, with all users consuming less than before, except for the HI lowlands households. This trend is evident when comparing the new values of monthly electrical consumption with the old ones shown in 5.1.

5.3.2. Analysis and comparison of the residential sector

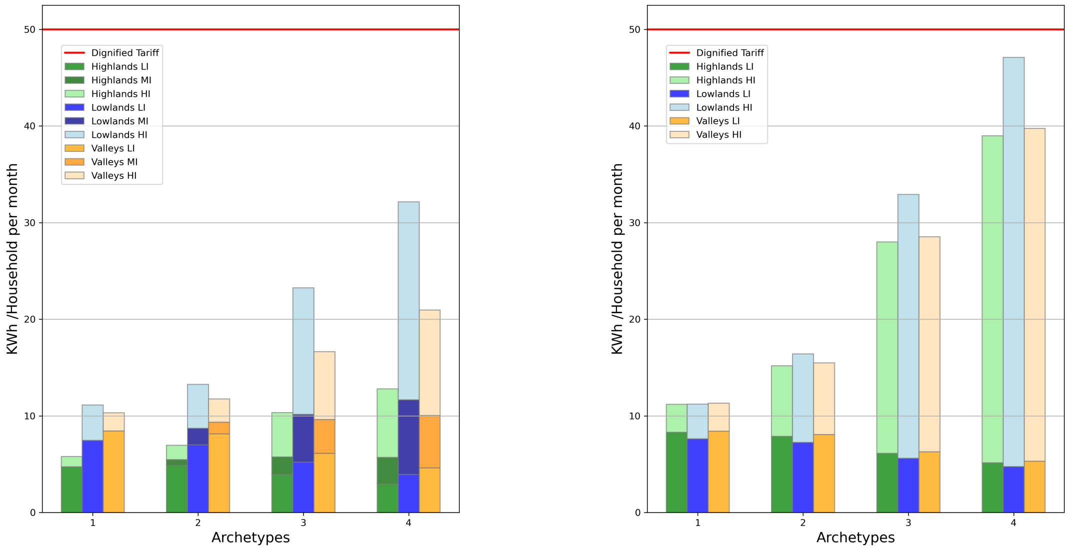


Figure 5.18: Residential comparison: monthly electrical consumption between regions and per income classes. On the left the improved results, on the right the old ones.

Figure 5.18 presents a comparison between the two distinct approaches for analyzing monthly electrical consumption per household across the four archetypes and for all regions. The figure provides a detailed breakdown of the contributions of high-income (HI), low-income (LI), and middle-income (MI) households to the residential load.

The specific display of the results used in the figure is justified by the same considerations as those applied in 5.1.2. The findings reveal noteworthy discrepancies between the two methods:

1. **Stages of development: UBN's influence on the demand.** As the poverty rate decreases across the four archetypes, the residential sector's electrical consumption increases significantly. Specifically, the fourth archetype's electrical consumption is almost twice that of the first archetype. However, when compared to previous results, the progressive and total increase in electrical demand across the stages of development has decreased notably for two main reasons:

    (a) The introduction of the MI residential user has led to a new procedure for determining the proportion of each household user, which has resulted in halving the number of HI households across archetypes 2, 3, and 4. As a result, high-income households, which have more electrical appliances and consume more electricity, do not make up a significant proportion of the population as before.

(b) The calibration of inputs necessary to match the measured data of ECRs for each region has led to a drastic decrease in monthly electrical consumption.

2. **Altitude: electrical demand comparison between different regions.** Unlike in the previous methodology regional differences start to manifest from the first stage of development especially for the highlands. In fact, ECRs relative to the highlands are considerably lower than in other regions. Regional disparities in electrical consumption can be observed across all archetypes, with the magnitude of differences increasing moving towards the last one. Indeed, the fourth archetype stands out with the highest consumption gap between regions, highlighting substantial disparities in electrical consumption.

   These differences primarily originates from the impact of climate variations on household electricity usage, as modelled in RAMP. Indeed, the presence of refrigerators also plays a significant role in determining electricity consumption levels, varying the proportion of households with fridges contributes to regional disparities. As a result, the lowlands region exhibits the highest electricity consumption across all archetypes, followed by the valleys, and then the highlands with the lowest consumption. Table 5.5 compares the monthly electrical consumption values between the two methodologies.

Monthly Consumption [KWh]	Lowlands	Highlands	Valleys
LI $_{old}$	7,68	8,31	8,36
LI $_{new}$	7,68	4,7	8,23
HI $_{old}$	88,32	68,915	73,61
HI $_{new}$	87	25,5	44
MI $_{new}$	33	9,95	21,9

Table 5.5: Monthly electrical consumption values comparison.

5.3.3. Yearly electricity consumption: break down per energy sector

Figure 5.19 provides a concrete example of the breakdown analysis of energy sector contributions to the yearly electrical consumption of a highland community comprising 500 people. Although the same analysis has been conducted for lowlands and valleys with the identical community size, only the highlands' results are shown for the sake of simplicity and because the remodelling is expected to have the most significant impact in the highland community.

Even though absolute consumption levels for IGAs and community services remain the same

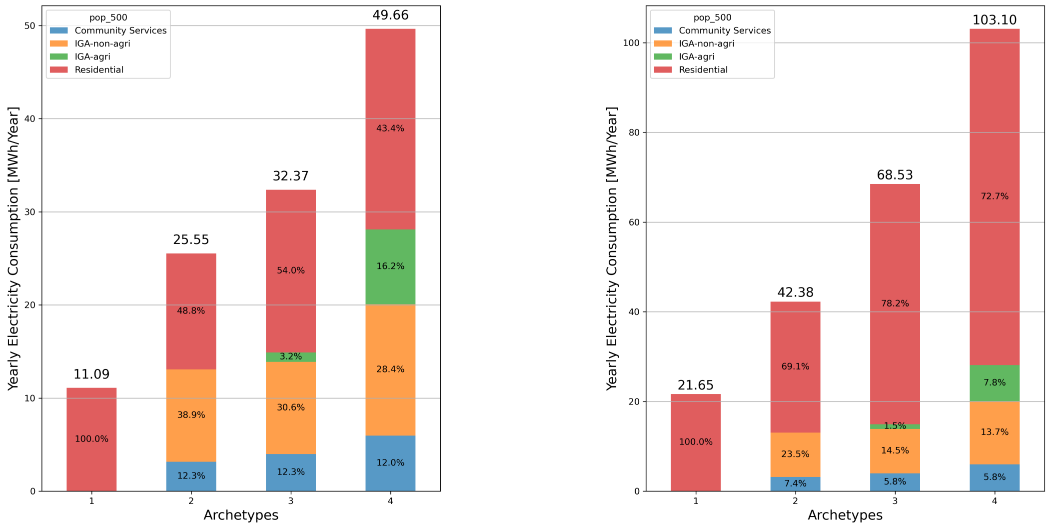


Figure 5.19: Consumption break down per energy sector: on the left the improved methodology's results, on the right the old ones.

as before, changes in the percentage contributions of energy sectors can be attributed to the decline in residential consumption. Additionally, the stronger regional differences observed previously (5.3.2) influence different behaviours with respect to the percentage of energy consumption attributed to each sector across the archetypes for each region. In particular, valleys and highlands regions, which have experienced the greatest decrease in residential consumption, have seen a significant increase in the contribution of IGAs. Especially in the fourth stage, due to the presence of transformation activities, the IGA's contribution reaches its highest levels. As altitude has diverse pronounced effects on the three regions each of their results are briefly described individually to delineate their specific findings.

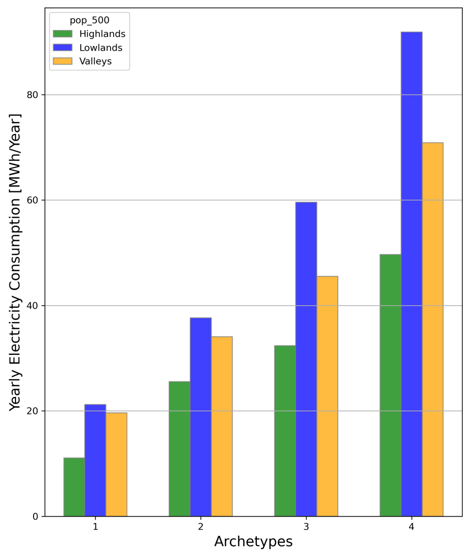
Highlands. Residential electricity consumption has reached its lowest levels of percentage contribution. Especially in the fourth archetype, the residential sector's share has dropped to a level that is comparable to that of the IGA sector, accounting for only 44 % of the total electricity consumption. This trend raises significant concerns regarding the current electrical demand modeling, particularly in the IGA sector, and its potential impact on the future system sizing. However, this issue will be addressed in detail later in this work.

Lowlands. Energy sectors exhibit a comparable trends to those of the previous methodology.

Valleys. Energy sectors shares exhibit a comparable behavior to those of the previous methodology, with one exception: the residential sector accounts for only 56 % of the total demand in the last archetype, while the IGA sector is at its highest with 35.5 %.

Overall, despite significant regional disparities, the residential sector remains the largest consumer of electricity in all regions. However, there has been a significant reduction in overall energy consumption across all regions due to the huge decrease of residential consumption. This trend is evident at the community level, as depicted in Figure 5.20, where the yearly consumption levels for different regions and stages of development are compared. For instance, the highlands region has experienced a nearly 50% decrease in annual consumption levels for all archetypes when compared to previous values.

Additionally, it is worth noting that comparable observations to those highlighted in section 5.3.2 regarding the impact of UBN and altitude can be discerned. Given that the residential sector is a primary contributor to the overall energy consumption, any modifications to it can significantly influence the total energy consumption, thereby revealing similar patterns to those observed in the solely residential sector analysis. For instance, the marked regional disparities in energy consumption are also evident in the total energy consumption at the community level.



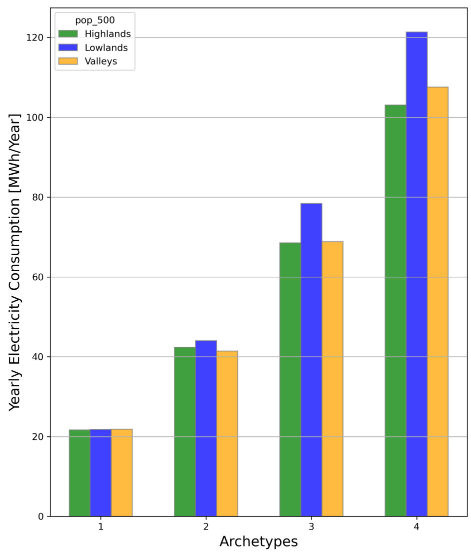


Figure 5.20: Yearly electrical consumption comparison between different methodologies: on the left the improved methodology's results, on the right the old ones.

5.3.4. Peak power per energy sector

Figure 5.21 presents an analysis of the peak power per energy sector of a highland community with 500 inhabitants across all. Some key differences are observed compared to the

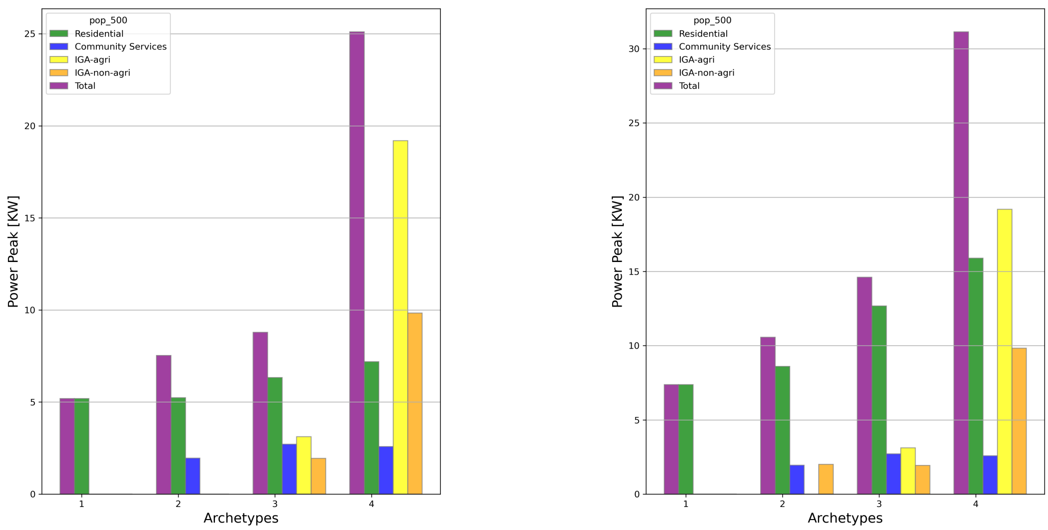


Figure 5.21: Peak power per energy sector: improved highlands results on the left, old residential modelling results on the right.

previous methodology. Firstly, the residential peak power does not double as the community transitions from the first to the last archetype, which is a significant change from the previous results. This reduction impacts the total peak power values, which are lower due to the remodelling of the residential sector. However, there is still a gradual increase in the residential power peak moving towards the last archetype, although it is significantly milder than before. The residential sector peak power remains the highest for the first three archetypes, but its relative weight compared to other energy sectors decreases, especially when compared with the IGA sector.

Secondly, when the community achieves energy sufficiency, the IGA sector's peak power surpasses that of the residential sector as it was happening before. However, the gap between the residential and IGA peaks is notably increased, especially for lowlands and highlands. Again, this significant contribution raises concerns about the current electrical demand modeling, particularly in the IGA sector, and its potential impact on future system sizing.

5.3.5. Main conclusions: improved methodology

By implementing an improved methodology, the new analysis has provided valuable insights into rural residential electrical consumption on a national scale, and has highlighted the key role of the validation procedure. Therefore, the updated methodology has yielded important findings that have significant implications:

1. Regional differences in electrical consumption and peak power have been more accurately identified revealing significant disparities between different contexts. The influence of altitude, as the most important driver linked to electrical consumption, has increased significantly.

2. Overall household electrical consumption has decreased substantially, due to both the inputs calibration procedure and the introduction of middle-income households.

3. The importance of IGAs has been shown to increase, particularly when energy sufficiency is achieved, as the residential sector's role in terms of both electrical consumption and peak power is reduced. This highlights the crucial role played by IGAs transformation activities in the community's total load.

5.4. Sizing results

5.4.1. First analysis

The first analysis focuses on how altitude affects the sizing process of hybrid mini-grid systems for rural communities that have achieved the energy sufficiency status. To conduct this analysis, we performed a linear optimization using MicrogridsPY as described in section 4.8 on three specifically selected communities. The three optimizations performed differed only in two inputs while keeping all the other techno-economic parameters fixed:

1. The load curve used which is dependent solely on altitude to isolate its impact while keeping other drivers and techno-economic parameters constant. It is worth remembering that more details about the load curves used as inputs are showed in table 4.6.

2. The solar irradiation, which varied based on the specific location of each community.

Table 5.6 provides the main outputs of the three optimized systems, which can be useful for a quick and preliminary techno-economic discussion.

The analysis revealed that in "Challa Arriba"(highland community), characterized by lower demand and power peak, the optimal mini-grid configuration mostly relies on PV panels and batteries to cover the energy consumption of the village. In fact, the system minimizes the use of diesel generators by relying more on battery banks, which are charged during hours of maximum solar radiation, to cover mostly the high-power peaks and day-night transitions. On the other hand, in "Manuel Ascencio Padilla" and "Tabacal" villages (the lowland and valley communities), characterized by higher demand and power peaks, gensets are used more

Description	Highlands	Lowlands	Valleys	Unit
NPC	105,44	202,95	151,99	kUSD
LCOE	0,2494	0,2595	0,2519	USD/kWh
INSTALLED CAPACITY				
PV panels	28,57	42,59	28,24	kW
Battery bank	85,99	96,15	74,34	kWh
Diesel Genset	3,50	8,80	6,36	kW

Table 5.6: Techno-economic outputs: First analysis.

intensively and the battery bank provides the needed flexibility to the microgrid. This allows the gensets to be used, together with batteries, to cover the high-power peaks and day-night transitions. From an economic perspective, the Net Present Cost (NPC) is the financial metric used to estimate the overall cost of an energy project by calculating the present value of all cash inflows and outflows over the project's lifetime. It takes into account the initial capital investment, maintenance and operational costs. In the context of an energy access project, such as a mini-grid solution, NPC is an important economic index as it helps to determine the feasibility and profitability of the project. It allows investors and decision-makers to compare different projects and make informed decisions about whether the project is financially viable. After comparing the NPC values of the three systems, it is clear that altitude plays a crucial role in determining a project's bankability and energy deployment strategies. This is proven by the substantial percentage difference between NPC, with the greatest variance found between lowland and highland estimates at approximately 63%. Therefore, factoring in altitude can significantly improve the precision and dependability of cost-benefit analyses for any project and electrification strategy. On the other hand, the LCOE values do not show significant differences.

5.4.2. Second analysis

In this second analysis the impact of residential sector remodelling is studied by comparing the sizing results obtained from the initial methodology implementation and the improved methodology. Even though the discussion of results is limited to the highland community, which is the most affected by the residential remodelling, the results for all communities are still presented in Table 5.7. The analysis shows that the system optimized with the old residential modelling needs to cover higher demand and power peaks, resulting in a more intensive use of mini grid's gen-sets, increased installed capacity of components, and subsequently higher NPC. In contrast, the system optimized using the validation results shows a significant decrease in NPC, emphasizing the crucial role of the residential remodelling in the improved methodology. As a prove of this concept, the percentage difference in NPC between the two systems is 64%. Furthermore, LCOE varies in the present analysis, showing a lower LCOE, indicating that meeting a higher demand had a more significant impact than the increase in the total cost of the system.

Description	Highlands	Lowlands	Valleys	Unit
NPC	205,12	255,22	217,50	kUSD
LCOE	0,2337	0,2470	0,2375	USD/kWh
INSTALLED CAPACITY				
PV panels	44,91	52,52	40,04	kW
Battery bank	112,81	94,35	75,29	kWh
Diesel Genset	7,95	11,48	10,10	kW

Table 5.7: Techno-economic outputs: Second analysis.

5.4.3. Third analysis

The third analysis focuses on examining how processing activities under the IGA energy sector impact the sizing process. We compare the results from the first sizing analysis with another system that excludes processing activities from the load curve to understand this impact. This analysis is limited to the highland's community and is presented in Table 5.8.

Description	Highlands no processing act.	Highlands	Unit
Net present cost	88,991	105,44	kUSD
Levelized Cost of Energy	0,2457	0,2494	USD/kWh
INSTALLED CAPACITY			
PV panels	19,1	28,57	kW
Battery bank	61,68	85,99	kWh
Diesel Genset	2,88	3,50	kW

Table 5.8: Techno-economic outputs: Third analysis.

The findings indicate a 17% difference in NPC percentage between the two systems, representing a significant additional cost. However, it's crucial to consider that this cost could potentially bring substantial benefits to the community's development, as discussed in subsection 4.5.10. It's worth noting that even though the cost of the system that considers processing activities is higher, the LCOE values between the two systems are nearly identical. This means that the final cost of electricity for the customer will not be affected, despite the higher system cost. Ultimately, a comprehensive analysis that takes into account all relevant factors, including costs, benefits, and feasibility, is necessary to make an informed decision on whether to include processing activities in the hybrid mini-grid system.

6 | Conclusions

The aim of this research is to develop a novel methodology that can provide a preliminary estimate of the electrical demand for non-electrified rural communities, considering their unique needs and context, to support the formulation of cost-effective electrification strategies of developing countries. To achieve this aim two main objectives have been pursued.

The initial objective focused on understanding the importance of an accurate electrical demand characterization, which must be linked to communities' unique energy needs and contexts, to guarantee a sustainable development. Addressing gaps in energy planning for developing countries, as identified in the literature, was fundamental. In fact, the scientific community has long focused on constructing highly detailed supply energy system models but has neglected to adequately characterize demand which represents a fundamental exogenous input for these models. As a result, many of these systems have proven unsustainable over time due to unreliable demand estimations that caused improper sizing. Additionally, the current energy models inadequately account for cross-sectoral and cross-disciplinary interactions. Therefore, the electrical demand characterization of rural Bolivian communities started with the re-conceptualization of the energy sufficiency concept. Our approach recognizes the inter-linkage between energy and all aspects of community life, including education, health, and social participation. It is tailored to the unique socio-economic factors of rural areas in developing countries and establishes a minimum level of energy services required to ensure dignified living conditions, enabling continuous economic and social development. Additionally, a special focus is given to the relevance of agricultural and transformation activities that are often neglected when it comes to energy access projects.

The second objective, developed considering the conclusions of the first section, focused on the load estimation of un-electrified rural communities using settlement specific socio-economic factors. This was achieved through a top-down approach, which creates load demand archetypes based on three main drivers: altitude, poverty level and community size. The resulting archetypes, designed to reproduce un-electrified rural communities, are valid at national level providing a comprehensive understanding of how different combinations of these three primary drivers impact electrical demand. The proposed archetypes offer an approach to modelling a community's complete structure, incorporating residential, community services, and IGAs (Income generating Activities) sectors. Consequently, to assess the electrical demand, we employed a bottom-up demand energy model (RAMP) that takes the archetypes as input and generates the annual load curve for each day of the year, producing 365 stochastic daily profiles at a one-minute time resolution. During this process, the analysis of load curves has revealed that households consistently contribute to over 70% of the total community electrical load. For this reason, we have decided to validate the residential sector modelling and archetype creation methodology by analysing real data on monthly electrical consumption from across Bolivia. As a result, the procedure improved accuracy and reliability of our methodology. Lastly, by applying our top-down methodology to three case studies, we have proved its major impact in determining the optimal sizing of hybrid mini-grid systems, particularly in terms of economic returns.

Estimating the load demand for non-electrified communities can be challenging due to the difficulty of gathering data from remote rural areas. To address this issue, the archetype approach provides a simplified method for quick and easy load estimates, serving as an alternative to more complex and less accurate load estimation techniques. In fact, this methodology can aid in identifying suitable locations, where more detailed and thorough assessments can start, improving the accuracy and efficiency of electrification planning. Although our top-down approach may not fully characterize demand around specific local needs, it offers a valuable tool for improving load input detail for energy models, if compared to standard cumulative daily or yearly load consumption tiers. This represents an important progress towards a more accurate load profile resolution while maintaining the straightforward nature of top-down approaches.

Our study has revealed that altitude, community size and structure, and the level of Unsatisfied Basic Needs (UBN) are key factors impacting the electrical demand curve in rural communities. Therefore, failing to account for heterogeneity within a country could result in inaccurate predictions of electricity demand, hindering the development of effective energy strategies. Moreover, this highlights the limitations of using nationwide electrical consumption standards for an entire country, as such standards fail to account for the diverse needs and circumstances of individual regions. In conclusion, this study has established the pressing need to focus on characterizing electrical demand and its pertinence in Bolivian rural areas. Consequently, our approach has highlighted the importance of accurately assessing load demand for effectively modelling energy system solutions, which can lead to cost savings, improved energy strategies, and increased sustainability of the assessed systems. Furthermore, the proposed methodology is meant to be flexible with the ability to adjust to changes in electrical demands, making it reusable in other contexts and countries.

6.1. Future work

This research study identifies several opportunities for further investigation and improvement. Firstly, to enhance the accuracy of results, it is necessary to address the limitations in the validation procedure. Currently, the procedure relies on monthly electrical consumption data across the entire country, but with low geographical resolution. To overcome this issue, more advanced techniques could be used for data analysis.

Secondly, our methodology offers customization and improvement opportunities, especially for energy users in the IGA and community sectors where data is often scarce. To increase the level of detail for these users, extensive field-validation could be leveraged to obtain more precise data and create more representative archetypes.

Lastly, integrating a database of observed consumption patterns in recently electrified communities could enhance load prediction. This reliable source of harmonized data can serve as a valuable asset for energy planners and improve the quality of input data during the archetype's creation process.

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A | Annex: Seasonal Trend Analysis

A.1. Seasonal Trend Analysis

To investigate whether seasonal trends exist in the electricity consumption of the residential sector, it is essential to study how electricity consumption ranges (ECRs) vary throughout the year. Seasonal changes, such as temperature fluctuations or different activity patterns, can affect households' electrical consumption and, in turn, expand or skew ECRs. Analyzing how the thresholds of each ECR change over the months can provide insights into seasonal trends.

To investigate seasonal trends in residential electricity consumption, these steps have been followed for each region considered:

1. Choose one ECR.
2. Determine the upper value that defines the ECR for each month.
3. Calculate the 75th percentile of all the upper values calculated in step 2. This value indicates the threshold above which electricity consumption is considered to exhibit seasonal behavior.
4. Compare the upper values for each month in the selected ECR to the threshold calculated in step 3. This comparison identify which months have significantly different levels of electricity consumption.
5. Repeat the procedure for all the ECRs.

By following these steps, you can determine if seasonal trends exist in residential electricity consumption and identify which months exhibit the most significant differences for the three segments of the residential sector identified : low,middle and high-income. However the existence of a seasonal trend is considered when: the number of consecutive months in which the delimitation value is surpassed are equal or higher than three. Otherwise, such months are considered as an anomaly that could have different meanings of which is difficult to give interpretations.

In the end, none of the anomalies identified were long-lasting enough to persist for three consecutive months, and as such, no seasonal trends could be defined. This outcome could be attributed to the fact that in countries like Bolivia, which are situated near the equator, the distinction between seasons is less distinct.

Moreover, anomalies were absent in only five months - March, July, August, November, and December - across all the different zones for all the ECRs simultaneously. For this reason, these months are considered the most representative of typical residential behaviour and will be used in future analyses due to this characteristic.

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Nomenclature

EMS Energy System Modelling

GTF Global Tracking Framework

HL Highlands

IEA International Energy Agency

IGA Income Generating Activities

$IRENA$ International Renewable Energy Agency

LL Lowlands

MIS Minimum Income Standard

MTF Multi Tier Framework

NPC Net Present Cost

SDG Sustainable Development Goal

$SEforALL$ Sustainable Energy for All

UBN Unsatisfied Basic Needs

VA Valleys

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Agli amici che ho avuto la fortuna di conoscere in questo anno di tesi. Da voi ho imparato molto.

Agli amici con cui sono cresciuto da che ho ricordo. Siete una seconda casa.

Ad Auriane che ho avuto la fortuna di incontrare in questo pazzo viaggio.