Integrating isolated communities into national energy planning models - a case study in Bolivia

Auteur : Arias Valentines, Roger
Promoteur(s) : Quoilin, Sylvain
Faculté : Faculté des Sciences appliquées
Diplôme : Cours supplémentaires destinés aux étudiants d'échange (Erasmus, ...)
Année académique : 2024-2025
URI/URL : http://hdl.handle.net/2268.2/23806

University of Liège
School of Engineering and Computer Science

Integrating Isolated Communities into National Energy Planning Models

A case study in Bolivia

Master's thesis completed in order to obtain the degree of
Master of Science in Energy Engineering
by **Roger Arias Valentines**

Supervisor: Prof. Sylvain Quoilin
Co-Supervisor: Claudia Sánchez Solís (ULiège)
Co-Supervisor: Pablo Jimenez Zabalaga (UCLouvain)

Academic year 2024–2025

Acknowledgments

First of all, I would like to say that this thesis represents the end, at least for now, of my studies. It closes a long period of my life in which I dedicated countless hours to engineering. After much effort and sacrifice, I can finally say that it has all been worthwhile.

I would like to express my deepest gratitude to my friend Pablo Viscarri, who has been the person that accompanied me the most throughout these years and with whom I share countless memories. I am also grateful to Pau Ollé, Sergi Plaja, and Pau Fiol, who made my university experience an unforgettable stage of my life. I also want to thank my lifelong friends, who made this journey lighter with the endless stories and anecdotes we have built together. I owe the greatest gratitude to my family, who have always given me their unconditional support throughout this process.

I would also like to sincerely thank my co-supervisors, Claudia and Pablo, for their constant support, guidance, and willingness to answer my questions whenever I needed it. I am equally grateful to all the people who made my stay in Liège such a memorable experience, from those with whom I shared endless hours in the study room to those who filled these months with unique moments that will forever remain in my memory.

The author acknowledges the use of Large Language Models (LLMs), specifically ChatGPT, to assist with grammar refinement, style editing, and translations.

Abstract

Universal electrification in Bolivia requires demand representations that are context specific and compatible with system-level planning. This thesis develops an open-source two-stage framework that generates high-resolution electricity demand for unelectrified rural communities with the RAMP stochastic bottom-up model and integrates those demands into a national optimisation with EnergyScope MultiCell. Municipalities are grouped into Highlands, Valleys, and Lowlands. Information on electrified and unelectrified households for the 2024 baseline is obtained from the Instituto Nacional de Estadística (INE). RAMP inputs cover households, community services, and income-generating activities under an energy-sufficiency premise. Minute-level series are aggregated hourly and mapped to EnergyScope end-uses. On the supply side the model is extended with new cells, technology options suited to remote contexts, a population-density criterion to select off-grid solutions, explicit electrical losses and a constraint that allows home-system batteries to charge only from PV Home Systems. Three snapshots for 2024, 2035, and 2050 quantify technology choices, costs, and emissions. Results show marked regional heterogeneity, for example higher cooling and food preservation needs in the Lowlands, and higher water heating and space heating needs in the colder Highlands. They also show a dominance of PV plus battery portfolios in remote supply, together with an important contribution from diesel systems that decreases over time, and non-negligible impacts on national costs when remote regions are included. The contribution is a reproducible pipeline that includes data, code, and modelling choices, links micro-scale demand formation with country-scale planning, and strengthens the realism of scenarios for universal, affordable, and low-carbon access in Bolivia.

Contents

List of Figures

List of Tables

1. Introduction

1.1 Background and motivation

Access to electricity is a fundamental enabler of development, directly impacting education, healthcare, economic productivity, and overall quality of life. Therefore, it is essential to guarantee access to electricity for everyone. Among the objectives of the 2030 Agenda for Sustainable Development, Goal 7 specifically aims to ensure access to affordable, reliable, sustainable, and modern energy for all. [4] This goal recognizes energy access as a critical factor for eradicating poverty and fostering sustainable development.

In many countries, including Bolivia, there is a significant disparity in electrification rates between urban and rural areas, with regions closer to urban centers considerably better served. Furthermore, Bolivia's highly dispersed and unevenly distributed population creates major challenges for national energy system planning, especially when it comes to extending infrastructure to remote and isolated communities. The country's complex geography, which includes mountainous regions, tropical forests, and vast lowlands, also complicates grid expansion efforts. As a result, providing reliable and affordable electricity to these areas often becomes economically unfeasible and requires alternative planning approaches based on decentralized solutions.

Given the persistent challenges faced by remote and rural communities in Bolivia, it becomes crucial to develop energy planning strategies that explicitly consider populations currently lacking access to electricity. Traditional energy planning frameworks often overlook these communities due to the absence of reliable consumption data, which results in their exclusion from future development scenarios. To address this gap, it is necessary to apply innovative modeling approaches that can simulate the demand of unserved populations and integrate this information into national energy planning processes, ensuring more inclusive and equitable outcomes.

1.2 The Role of Energy System Models in Electrification Planning

Energy system models are crucial tools that provide insight and structured analysis of the supply and demand of energy across different regions. Initially developed to address concerns over energy security and economic planning, their importance has grown significantly due to new twenty-first century challenges such as climate change, the integration of renewable energy, and the need for sustainable development. These models allow the people in charge to explore different technological and economical ways, helping to design robust strategies for future energy systems. By simulating future demand and supply scenarios, they support the optimization of resource allocation, the reduction of greenhouse gas emissions, and the improvement of energy system resilience. As the energy landscape becomes increasingly complex and decentralized, energy system modeling continues to play a vital role in informing national and international energy policies. [5]

Although energy system models have become increasingly sophisticated, an important limitation remains regarding the inclusion of populations without reliable energy consumption data. In many developing regions, including Bolivia, remote and isolated communities often lack the historical demand records needed by conventional modeling approaches. As a consequence, these communities are usually excluded from national energy planning exercises, which primarily focus on optimizing supply for existing, and well known demand centers. This exclusion not only denies energy access to these regions, but the lack of investment also deepens their marginalization. To achive inclusive electrification strategies, it is essential to incorporate simulated demand for rural and isolated zones into energy system models, ensuring the development of all population, not just for already connected areas.

This highlights the crucial role that energy system models play in planning a country's energy infrastructure and development. For this reason, in this thesis, such models will be used to promote comprehensive planning that considers all areas, not only those that are already electrified.

1.3 The Bolivian Context

1.3.1 National Context: Bolivia

Socio-economic and Demographic Overview

Located in South-America, Bolivia is a landlocked country with a total area of 1.098.580 km^2 [6], ranking it among the larger countries on the continent by area. In spite of its size, the population is comparatively small at about 10,3 million [7], giving it a population density of about 11 inhabitants for each square kilometer. The disproportionate population dispersion poses certain difficulties in the development of infrastructure as well as the provision of public utility services, particularly for rural areas.

Economically, it was ranked at number 96 worldwide by Gross Domestic Product (GDP) volume. In 2023, it had a GDP per capita that was at an estimated 3.433 €, placing it at the lower end of the global scale at number 130 among a total of 196 nations, reflecting a propensity for low overall living standards. In 2022, its public debt was 33,69 billion €, translating to 80,1% of the GDP, meaning that the country faces severe challenges regarding economic development that directly affects the energy sector. [6] Bolivia's challenges can also be seen reflected to its Human Development Index (HDI). The index developed by the United Nations indicates a low quality of life. Additionally, a high level of corruption is perceived in the public sector.

This context is very important for understanding the current state of development and the importance of strategic electrification planning. Addressing energy access in Bolivia is not only a technical challenge but also a fundamental step towards improving quality of life and enabling sustainable development. [6]

To provide additional geographic context, Figures 1.1a and 1.1b summarize Bolivia's physical relief and administrative structure. Figure 1.1a highlights the main elevation zones while Figure 1.1b shows the political division into departments, the country's highest-level administrative units.

(a) Physical map of Bolivia

(b) Political map of Bolivia

Figure 1.1: Maps of Bolivia [1]

Electrification Challenges and Development Goals

Despite Bolivia's progress in expanding electricity access over the past two decades, significant disparities remain between urban and rural areas. While most urban households are connected to the national grid, many rural and remote communities still lack reliable access to electricity. These gaps are largely due to the country's challenging topography, low population density in vast rural regions, and the high per capita cost of infrastructure deployment in those areas. Additionally, technical limitations in transmission and distribution networks further restrict coverage in certain areas.

These electrification gaps are not merely a technical concern, they have profound implications for development, limiting access to education, healthcare, and income-generating opportunities in underserved areas. Addressing these challenges requires more than infrastructure investment: it demands a coordinated, data-informed strategy that integrates rural communities into national energy planning. Given the complexity and diversity of Bolivia's geography and settlement patterns, tailored approaches are essential to ensure equitable and sustainable progress.

1.3.2 The Bolivian Electric Grid

The Bolivian electric sector has undergone substantial investment in generation and transmission over the past decade, especially following major blackouts in 2010. However, structural challenges persist due to the lack of a modern energy policy and regulatory framework. The majority of generation is still fossil-fuel based, with natural gas accounting for more than 60% of output. Additionally, while export potential exists, geopolitical and infrastructure limitations have delayed integration with neighboring countries' grids.

Understanding the configuration of Bolivia's power system is essential to evaluate its current limitations and future potential. The following sections describe the structure and characteristics of the country's electricity supply, which is divided into two main systems:

the National Interconnected System (SIN), which covers the main urban and industrial regions, and the Isolated Systems (SA), which provide electricity to remote and dispersed areas not connected to the national grid. [8]

SIN: Interconnected National System

The National Interconnected System (SIN) is Bolivia's main electric power system, integrating the generation, transmission, and distribution infrastructure across eight departments: La Paz, Santa Cruz, Cochabamba, Oruro, Chuquisaca, Potosí, Beni, and Tarija. It includes most of the country's demand centers and allows energy exchanges between regions, improving reliability and dispatch optimization.

The SIN is structured into four historical regions (North, Central, South, and Eastern), each with different generation characteristics. For example, the North (La Paz) is dominated by run-of-river hydroelectric plants, while thermal generation is prevalent in the Eastern area (Santa Cruz). The Central and Southern regions combine hydro with reservoir and thermal sources [9].

The high-voltage transmission backbone, known as the Sistema Troncal de Interconexión (STI), enables the bulk transport of electricity between these regions. The system is managed under the Wholesale Electricity Market (MEM), where agents trade energy under spot and reference prices. The SIN plays a fundamental role in the country's energy planning and is central to future electrification and decarbonization strategies.

Figure 1.2 shows the structure of the National Interconnected System (SIN), highlighting the main transmission corridors and generation nodes across Bolivia. The system connects most of the country's major urban and industrial areas through a high-voltage backbone, enabling energy exchange between different regions. The figure provides a spatial overview of how Bolivia's electric infrastructure is organized within the SIN.

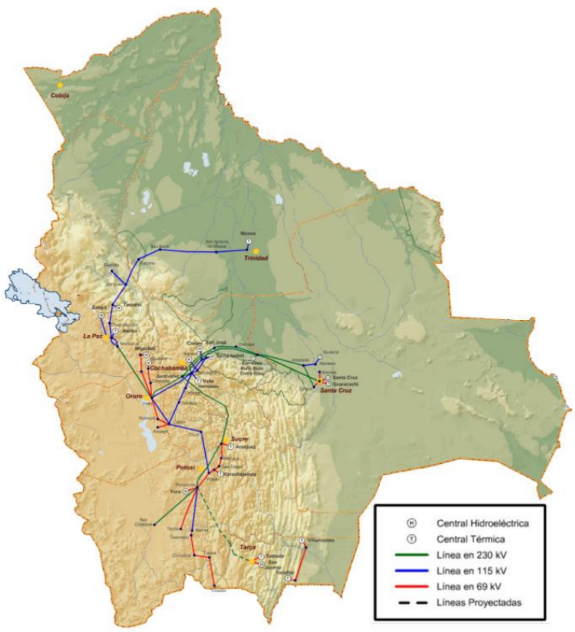

Figure 1.2: SIN Map [2]

SA: Isolated Systems

Apart from the National Interconnected System, Bolivia also relies on a number of isolated systems (Sistemas Aislados, SA) to meet the electricity needs of remote populations. These systems are not connected to the SIN, meaning they operate autonomously and are not part of the national energy dispatch or transmission infrastructure.

Some of these isolated systems serve relatively dense local populations and include internal distribution networks that ensure basic electricity supply for households and small businesses. However, the lack of interconnection with the national grid limits their operational flexibility, increases costs, and reduces reliability.

Figure 1.3 shows the location of generation plants that contribute to the SA. As illustrated, these systems are typically found in areas that the SIN does not reach, particularly in the Amazon region and the southeastern lowlands, reinforcing the need for alternative electrification strategies in these territories.

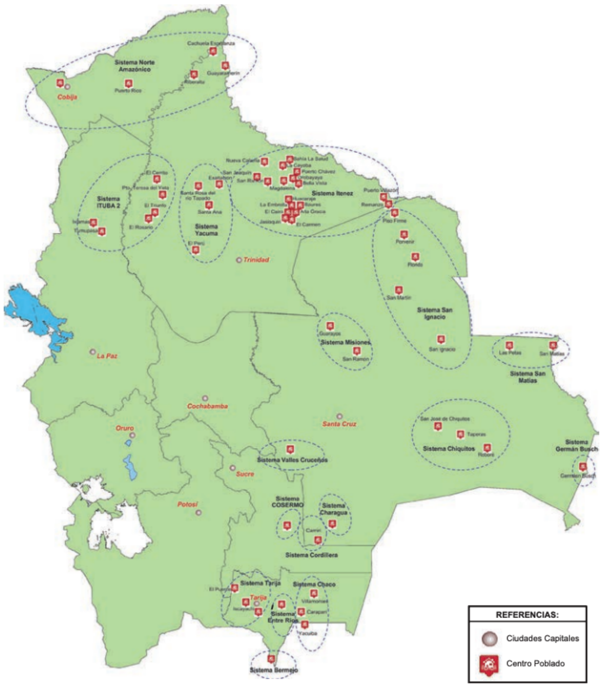

Figure 1.3: SA Map [2]

Role of Renewable Energy in the current system

Bolivia's current energy matrix is still predominantly based on fossil fuels, particularly natural gas, which accounted for 79.62% of primary energy production in 2023. However, in recent years the country has made efforts to diversify its energy supply through the gradual incorporation of renewable sources.

In terms of primary energy, renewable sources such as biomass, hydro, wind, and solar represented a combined 9.12% in 2023, up from 7.10% in 2019. Within this group, biomass remains the most significant, contributing 7.18%, followed by hydro (1.42%) and a growing share of solar and wind (0.52%).

In the electricity generation sector, the contribution of renewable energy also increased. From 2019 to 2023, the share of solar and wind energy in electricity production grew from 2.53% to 7.10%, indicating a positive shift toward clean energy sources. This transition is framed within the government's broader energy strategy, which emphasizes environmental sustainability and energy sovereignty. [10]

Despite challenges the growth in non-conventional renewables is evidence of a national commitment to transition the energy sector. These advances align with strategic planning instruments such as the PDES 2021–2025 and the Agenda Patriótica 2025.

1.3.3 Progress and Challenges in Electricity Access

In recent years, Bolivia has made significant progress in expanding electricity access, particularly in rural areas. This progress is documented in the Plan de Desarrollo Económico y Social (PDES) 2021–2025 [3], a national planning instrument that sets medium-term development goals and policy priorities across all sectors, including energy.

As shown in Figure 1.4, Bolivia has made considerable progress in household electricity coverage between 2006 and 2020. While urban areas have nearly universal access, rural areas still lag behind, highlighting the importance of continued efforts to close the electrification gap. Despite these improvements, several structural challenges persist. The

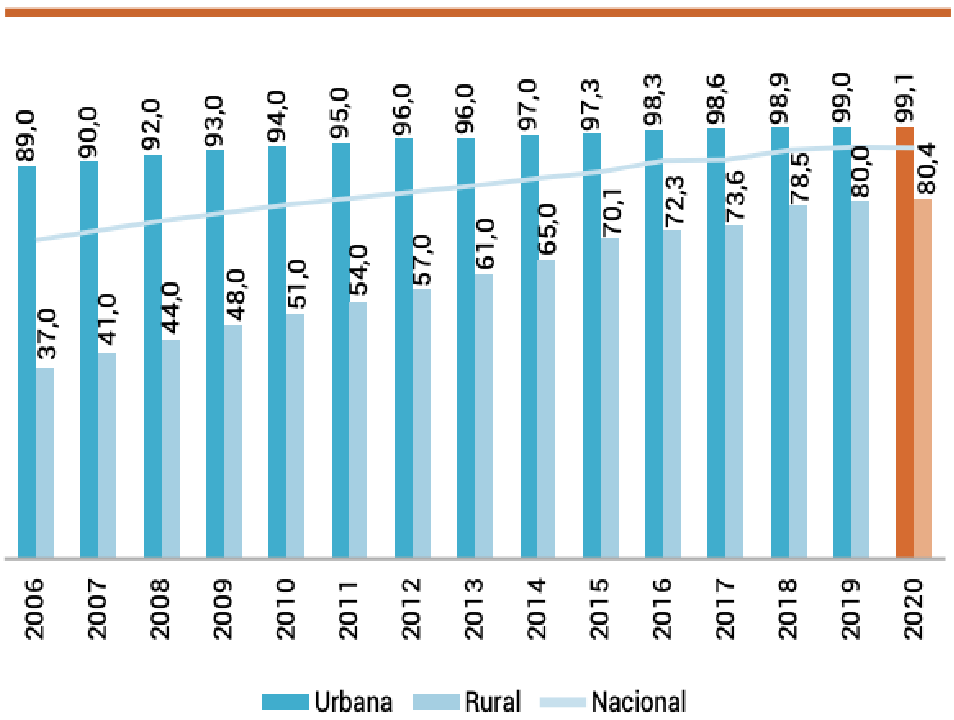

Figure 1.4: Electricity coverage in urban and rural households in Bolivia, 2006–2020 [3].

expansion of the grid has slowed in recent years, and many remote or dispersed communities continue to lack access to reliable electricity. This is due to both technical constraints, such as difficult terrain and high connection costs, and socioeconomic factors including low population density and limited local infrastructure.

The PDES recognizes that addressing these challenges requires a dual strategy: continuing the expansion of the national grid where feasible, and promoting decentralized electricity solutions in areas that remain isolated. These efforts aim to strengthen equity in access to energy and to support broader development in underserved regions.

1.4 Objectives

The main objective of this work is to integrate isolated communities without connection to the Bolivian electricity grid into national energy planning, so that they are explicitly considered and have the opportunity to develop on an equal footing with the rest of the country, without remaining marginalised.

To achieve this main objective, it is necessary to define a set of specific objectives.

Objective 1:

Due to the lack of data on the energy demands of areas that are not connected to the grid, it is necessary to devise a way to obtain this information, absent from official sources, and to generate annual demand profiles for these zones, taking into account climatological and temporal variations that affect demand.

Objective 2:

Determine how the energy demands of areas that are not connected to the grid or are unelectrified can be met. This requires identifying the technologies that would generate the energy needed to satisfy the demands of isolated areas.

Objective 3:

Integrate these isolated areas into national energy planning in order to assess the costs associated with their integration, the share of national energy demand they would represent, and their environmental impact.

Objective 4:

Ensure that this work serves as a basis for future studies by creating a methodology that can be replicated in different contexts, and by providing contributions to the Bolivian energy sector that can support subsequent research in the country.

1.5 State of the Art

Access to reliable and affordable energy is a key driver of development, yet millions of people in rural and remote areas still lack basic electricity services. Planning for the electrification of these areas presents significant challenges, especially in contexts where reliable data is scarce and conventional models fall short in capturing local complexity. In this context, understanding how existing tools can support more inclusive energy planning is essential.

This section presents a critical review of the current literature and modeling frameworks relevant to rural electrification in developing countries, with a particular focus on Bolivia. It is structured around two key components of the electrification planning process: the estimation of electricity demand in unserved areas, and the system-level optimization of energy supply to meet that demand. Both aspects are crucial in ensuring that energy strategies are technically sound, socially equitable, and economically feasible.

First, the section explores how bottom-up and stochastic modeling approaches, such as RAMP, are used to simulate energy demand in rural contexts. It reviews their strengths, limitations, and previous applications in Bolivia. Second, it examines energy system optimization tools, with a focus on the EnergyScope model and its regional adaptation to the Bolivian context. Finally, the chapter identifies the main gaps in existing research and explains how this thesis contributes to bridging them.

1.5.1 Rural Electrification and Demand Challenges

Despite global progress in expanding electricity access, rural electrification remains a major challenge, particularly in low- and middle-income countries. In many of these contexts, the combination of geographic isolation, low population density, and limited infrastructure makes the deployment of conventional grid solutions technically and economically difficult. As a result, rural populations are often left out of national energy plans or rely on unsustainable and unreliable energy sources.

Bolivia is no exception. In remote areas, the lack of detailed demographic and energy data further complicates planning efforts, making it difficult to assess demand and evaluate viable supply options. These limitations have led to electrification strategies that tend to prioritize urban zones, leaving many rural areas without concrete long-term solutions.

Addressing rural electrification in a more inclusive and strategic way requires tools that can overcome data scarcity and adapt to local realities. In this context, modeling approaches that allow for disaggregated demand estimation and regionalized planning become essential. The following sections review the main tools used for this purpose and assess how they have been applied in the Bolivian context.

1.5.2 Modeling Energy Demand in Remote Areas

Stochastic Approaches and the RAMP Tool

Accurately modeling energy demand in remote and off-grid areas presents a significant challenge due to the lack of reliable consumption data. Traditional approaches often rely on deterministic assumptions or empirical correlations that fail to capture the variability and complexity of user behavior, especially when it comes to thermal loads or appliances with irregular duty cycles.

To address this limitation, Lombardi et al. introduced RAMP (Remote-Areas Multi-energy systems load Profiles), an open-source bottom-up stochastic model specifically developed to generate high-resolution load profiles in remote areas [11]. The model is designed to work effectively in contexts where only limited and uncertain input data, such as that obtained through field interviews, is available. This makes it particularly suitable for energy access planning in underserved regions.

RAMP enables the simulation of both electric and non-electric demands, by allowing detailed modeling of appliance behavior. One of its most innovative features is the capacity to define and modulate appliance duty cycles over time, capturing the effects of user habits and environmental conditions on load patterns.

The authors validated RAMP using data from the off-grid hybrid microgrid of El Espino, Bolivia. Results showed that the model could reproduce measured demand profiles with high accuracy, achieving errors below 3% in key indicators, significantly outperforming previous models like LoadProGen [11].

By combining adaptability, transparency, and stochastic depth, RAMP fills a crucial gap in the modeling of energy demand for remote areas. Its open-source nature further enhances its flexibility, enabling users to simulate extreme or future-use scenarios that are essential for robust energy planning.

Demand Simulation in Bolivia

The RAMP tool has been previously applied to simulate electricity demand in rural Bolivian communities, as demonstrated in the work of Sánchez et al. [12]. In this study, the authors developed tailored RAMP inputs for communities of 500 inhabitants located in different regions of the country. These scenarios were designed to reflect increasing levels of poverty alleviation and energy access, ranging from minimal infrastructure to communities with extensive public services and productive activities.

The model accounts for three main energy-consuming sectors: residential services, community services, and income-generating activities (IGA). It also incorporates contextual information such as geographic location or poverty level. Notably, the level of poverty directly influences the presence of certain appliances and services. For instance, refrigerators, water supply systems, and community lighting are more prevalent in communities with lower poverty rates. This structure enables the simulation of multiple demand profiles that realistically reflect the diversity of rural conditions.

While this approach allows for a detailed simulation of a single community, the authors note that future work should extend the methodology to model multiple communities simultaneously. Such an extension would better support regional planning and facilitate the design of coordinated electrification strategies that capture the diversity of Bolivia's rural areas.

1.5.3 Energy System Optimization Tools

In recent years, several tools have been developed to support energy planning through system-level optimization. These tools are essential to evaluate which combinations of technologies and energy sources can meet future demand under economic, environmental, and technical constraints. They are particularly relevant for long-term planning and decision-making in the context of energy transitions.

Among these tools, *EnergyScope* and its multi-cell extension have gained attention for their capacity to model national and regional energy systems using open data and reproducible methods. These models are designed to simulate energy flows, technology investments, and emissions over long time horizons, considering multiple sectors and energy carriers.

EnergyScope MultiCell extends the original model by allowing multiple interconnected regions to be represented, making it possible to capture geographic diversity, resource distribution, and potential exchanges between areas. Its formulation is based on linear optimization, and it has been applied in a variety of academic and policy-relevant studies.

Given its capabilities and open-access nature, *EnergyScope MultiCell* has been used in recent research involving regional energy planning, including applications to Bolivia. The following sections review its main features and how it has been applied to support energy strategy design in the Bolivian context.

EnergyScope MultiCell

This model extends the original *EnergyScope* framework by allowing the simulation of energy systems divided into multiple geographic regions, each with different characteristics, while enabling interaction between them.

A clear example is presented by Thiran et al. [13], who apply the model to Italy, dividing the country into three macro-regions with distinct demand profiles and renewable resource availability. Their results show how regional modeling improves realism compared to single-node approaches, since each area has specific needs and can exchange energy with neighboring ones. This configuration better reflects how energy systems operate in practice, where spatial diversity plays a key role in infrastructure planning and technology deployment.

Another relevant application is found in the study by Jacquemin et al. [14], where the model is used to analyze decarbonization scenarios for Western Europe. The continent is divided into multiple zones that interact through energy flows, including cross-border electricity and hydrogen networks. This study focuses on exploring the potential of renewable fuels in reaching net-zero emissions by 2050, and also includes a techno-economic evaluation of the system costs associated with different energy strategies. It illustrates how *EnergyScope* can be used to assess both technological feasibility and economic implications in large-scale planning.

These studies show how EnergyScope and its variants can be adapted to a wide range of spatial and temporal scales, making them valuable tools for supporting energy policy design in both national and international contexts.

EnergyScope in Bolivia

In one of the most comprehensive applications of EnergyScope to a developing country, Jimene Zabalaga et al. [15] developed a national energy transition model for Bolivia by adapting the EnergyScope Pathway framework. The resulting model, known as EnergyScope Pathway-BO, simulates the Bolivian energy system from 2021 to 2050 and explores long-term decarbonization strategies using open-source methodologies and publicly available data.

The study implements a detailed characterization of energy demand across 17 categories, including residential, industrial, transport, agriculture, and public services. The model is calibrated to Bolivia's current energy system, which remains heavily dependent on fossil fuels and lacks a unified long-term transition strategy.

Three energy transition scenarios are analyzed: Business as Usual (BAU), National Energy Policies (NEP), and Net Zero Emissions (NZE). These scenarios incorporate government targets, demographic and economic forecasts, and sector-specific constraints. The results show that only the NZE scenario achieves full decarbonization by 2050, mainly through extensive electrification of end-uses and deployment of renewable energy technologies such as solar, wind, hydro, geothermal, and bioenergy. Moreover, the NZE scenario results in the lowest total system cost over the simulation horizon, due to the reduction in fossil fuel imports and operational savings.

Importantly, the model also accounts for Bolivia's existing power grid infrastructure, including the interconnected national system (SIN) and isolated grids (SA). This contextualization ensures that the results are grounded in real-world energy system limitations and possibilities.

1.5.4 Identified Gaps and Thesis Contribution

The previous sections have reviewed the main tools and studies relevant to this thesis, including the use of RAMP for modeling electricity demand in unelectrified rural areas and the application of EnergyScope to the Bolivian energy system. Although these studies provide a strong foundation, there are still important gaps that this work aims to address.

Most existing applications of RAMP focus on individual communities or specific regions, limiting their scalability to national planning. Similarly, the Bolivian adaptation of EnergyScope Pathway does not currently include demand from unserved rural areas, which results in a planning framework that excludes a significant portion of the population.

This thesis contributes to bridging that gap by integrating simulated demand profiles from unelectrified areas across the entire Bolivian territory. Instead of focusing on selected case studies, demand estimation is extended to all non-electrified regions, covering different geographic zones and population densities. These new demand inputs, generated using RAMP, are then incorporated into a customized version of EnergyScope MultiCell.

By adding new cells representing currently unelectrified areas, the model provides a more inclusive picture of Bolivia's energy needs. This enables the simulation of national-scale electrification scenarios that take into account both existing and currently excluded regions. The results include optimized technology mixes, associated emissions, and investment costs required to achieve full electrification.

This thesis combines two complementary tools: a bottom-up demand model, which estimates energy needs from household-level characteristics, and a national optimization model that plans energy supply across multiple regions. This integration allows for the inclusion of unelectrified areas in long-term planning and supports a more equitable and realistic electrification strategy for Bolivia.

2. Modeling Framework

2.1 Methodology

2.1.1 Overview of the approach

The methodology adopted in this thesis is designed to address the complex challenge of planning electricity access for isolated and rural communities in Bolivia. This is particularly relevant in contexts where detailed consumption data is limited, electrification levels are low, and traditional energy models fail to capture regional disparities or infrastructural limitations.

To overcome these challenges, a **multi-step modeling framework** is proposed, combining the capabilities of two open-source tools: **RAMP** and **EnergyScope Multicell**. Each tool plays a specific and complementary role in the modeling process:

- **RAMP**, is used to generate high-resolution, spatially disaggregated energy demand profiles for unelectrified areas.
- **EnergyScope Multicell**, adapted to the Bolivian context, is used to simulate the national energy system, including supply-side technologies and planning decisions, now extended to incorporate decentralized electrification options.

These tools are integrated to support a coherent and flexible methodology, tailored to the Bolivian case, and capable of accounting for regional demand heterogeneity as well as infrastructure and technology constraints. The overall objective is to evaluate realistic and sustainable electrification strategies, and to ensure that currently unelectrified zones are effectively included in national energy planning.

The following sections describe, in detail, each step of the proposed methodology.

1) Data Collection

The first crucial step in the methodology is the collection and organization of relevant data. This phase is foundational to the entire modeling framework, as it enables the identification and characterization of unelectrified households, communities, and infrastructures that must be considered in this study. Given the lack of direct measurements or official records of energy demand in these regions, the data gathered in this step serves as the basis for estimating future energy needs and designing appropriate electrification strategies.

A key challenge is that these unelectrified areas are often not included in national energy databases, and demand profiles are typically unavailable. Therefore, indirect indicators — such as population, household density, climate, and infrastructure — must be used to infer potential demand levels.

To ensure consistency throughout the analysis, all data are spatially disaggregated and categorized by the three macro-regions defined in this thesis: the Highlands, the Lowlands, and the Valleys. Consequently, it is essential to organize the data at the municipal level and assign each municipality to its corresponding region.

Once the required data have been collected and classified according to regional affiliation, the methodology can proceed to the modeling of demand and simulation of electrification scenarios.

2) Demand Modeling

The first step in generating realistic energy demand profiles is to define the key sources of electricity consumption in rural and isolated areas. These consumption sources are then represented in the modeling tool RAMP, which allows for bottom-up estimation of hourly energy needs.

The primary source of electricity demand is the household, which accounts for the majority of consumption in off-grid settings. However, to more accurately reflect the real energy use in rural communities, additional infrastructures are also considered. These include public lighting, health centers, schools, small shops, and other essential services. The inclusion of these infrastructures aims to capture the broader socio-economic context of rural electrification and to avoid underestimating system requirements.

Each of these infrastructure types is modeled individually and classified by region, in line with the regional division used throughout this thesis (Highlands, Lowlands, and Valleys). Furthermore, the configuration and density of infrastructures vary slightly between regions to reflect local characteristics and development patterns.

Within each infrastructure, specific electric loads are modeled separately (e.g., lighting, refrigeration, ICT). For some of these loads, especially those related to space conditioning or climate-sensitive uses, seasonal and climatic factors such as temperature and time of year are also taken into account. This results in hourly demand profiles that are both regionally differentiated and reflective of realistic daily and seasonal usage patterns.

3) Demand Generation Using RAMP

Once all electricity-consuming infrastructures and appliances have been defined and parametrized, the simulation is executed using RAMP. This step generates electricity demand profiles for each type of infrastructure, disaggregated by region and by consumption category.

The results include high-resolution time series, with values provided at one-minute intervals for an entire year. These profiles capture the aggregated behavior of the modeled infrastructures and reflect both seasonal and daily variability in electricity use.

This level of detail allows for greater flexibility in analysis and enhances the compatibility of the output with the EnergyScope model, which is addressed in the following step.

4) Integration of Demand into EnergyScope

The next step involves incorporating the demand profiles generated by RAMP into the EnergyScope model. While RAMP, in our case, produces detailed electricity demand data, EnergyScope operates based on end-use energy demands. Therefore, a transformation is required to convert the electricity demand values into sectoral energy demands that align with EnergyScope's input structure.

This conversion is possible thanks to two key aspects. First, RAMP provides disaggregated demand profiles by end-use category, such as lighting, refrigeration, or heating. Second, EnergyScope includes specific coefficients and conversion factors within its codebase, which are used to translate electrical loads into end-use energy terms. By applying these predefined parameters, all electricity demands from RAMP are systematically reclassified into EnergyScope-compatible energy demands.

Additionally, EnergyScope requires input data in the form of hourly annual time series. Since RAMP outputs data at one-minute resolution, the demand profiles must be aggregated to an hourly format. This is achieved by averaging or summing the minute-level data for each hour of the year, resulting in the required time series format for simulation within EnergyScope.

5) Adaptation of the EnergyScope Model for Unelectrified Regions

This thesis builds upon the existing implementation of the EnergyScope Bolivia model, available as an open-source repository [16]. The current version represents Bolivia's national energy planning context, focusing on the main interconnected systems. To incorporate isolated and unelectrified areas into long-term planning, the model is extended to include the new regions addressed in this study.

For each added region, the corresponding energy demand profiles are introduced, alongside the region-specific resources and available technologies. These new areas are modeled as independent cells within the EnergyScope Multicell structure, allowing them to have their own energy balance while being evaluated in the context of the national system.

Several new technologies are added to better reflect the conditions and electrification strategies appropriate for rural and isolated environments. This includes solar home systems and isolated diesel generators. Each of these technologies is modeled based on techno-economic parameters derived from recent literature and field studies.

In order to properly simulate these additions, new equations and constraints are implemented in the EnergyScope codebase. These modifications ensure that the model can handle decentralized generation, technology-specific losses, and constraints on electrification coverage. Further code improvements are also introduced to enable new functionalities and ensure consistency with the updated modeling framework.

6) EnergyScope Simulation

Once the new regions and corresponding demand, resources, and technologies have been integrated into the model, the EnergyScope simulations are executed to determine optimal electrification strategies. These simulations provide insights into which technologies should be deployed in each region, as well as the associated investment costs, operational expenses, and greenhouse gas emissions.

Simulations are performed not only for the base year (2024), but also for two future horizons: 2035 and 2050.

The results of these simulations allow for the comparison of electrification pathways over time, highlighting how technological deployment, costs, and environmental impact evolve across different planning horizons.

7) Result Analysis

After running the simulations, the results are analyzed to understand how the unelectrified regions behave under different electrification scenarios. Key outputs such as energy mix, technology deployment, costs, and emissions are examined.

These results are then compared with the existing national scenario to evaluate the overall impact of integrating rural regions into the energy planning framework. This allows for estimating the additional efforts and investments needed to achieve universal access to electricity in Bolivia.

Figure 2.1 shows a schematic summary of the methodology.

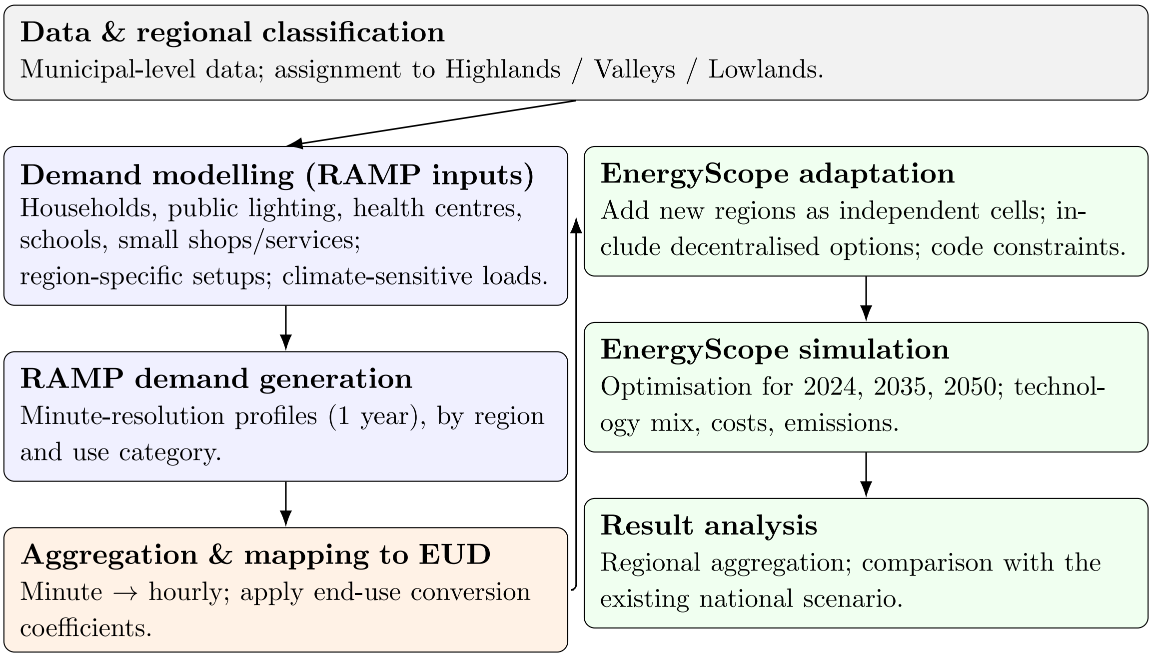

Figure 2.1: Section 2.1 methodology (schematic).

2.2 Data Collection and Processing

2.2.1 Zone Division

Climatic zoning using K-Medoids clustering

To classify the municipalities of Bolivia into climate-based regions, a machine learning approach was applied. Specifically, the K-Medoids clustering algorithm was used to identify groups of municipalities sharing similar environmental characteristics. This method was preferred over K-Means due to its robustness against outliers, as K-Medoids selects actual data points as cluster centers (medoids), rather than computing centroids based on mean values.

The input dataset for the clustering included three variables per municipality:

- **Mean ambient temperature**, extracted from the Renewables Ninja platform [17].
- **Relative humidity**, obtained from the Copernicus Climate Data Store [18].

- **Altitude**, also sourced from Renewables.ninja [17].

All features were normalized prior to clustering to ensure comparability. The number of clusters was set to $k = 3$, in line with the well-known climatic division of Bolivia into Highlands, Valleys, and Lowlands, as commonly adopted in related studies on rural areas of the country [12, 19].

The K-Medoids algorithm aims to minimize the total dissimilarity within each cluster, defined by the following objective function:

$$\min_{M} \sum_{i=1}^{k} \sum_{x \in C_i} d(x, m_i) \tag{2.1}$$

where

- k is the number of clusters,
- C_i is the set of data points assigned to cluster i,
- $m_i \in C_i$ is the medoid of cluster i, i.e., the most centrally located point,
- $d(x, m_i)$ is the distance between data point x and medoid m_i, typically computed using the Euclidean distance.

In this context, each data point x is a vector composed of normalized values of mean temperature, relative humidity, and altitude. The clustering was implemented in Python; the objective above is the standard formulation used throughout.

This clustering served as the basis for regional differentiation in demand modeling, enabling more accurate representation of climatic and socioeconomic variability across the country. The results are shown in Fig. 2.2, where each municipality is included in its region.

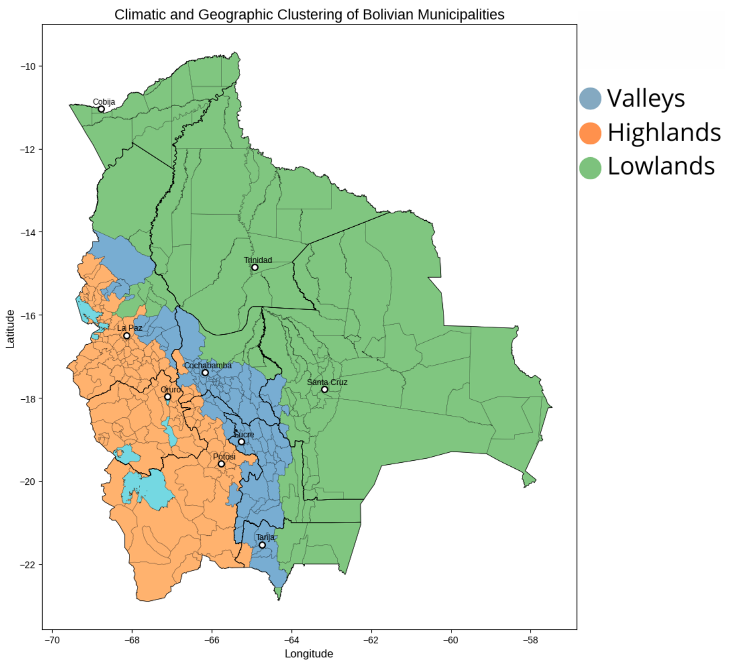

Figure 2.2: Zone divisions

Climatic characterization of the three zones: Broadly, the *Highlands* (Altiplano) are the coldest region, with low mean temperatures, larger diurnal ranges, and generally lower humidity. The *Lowlands* (Amazon and Chaco plains) are the warmest, with high mean temperatures and higher humidity in the north–east that becomes drier toward the south–east. The *Valleys* present intermediate, temperate conditions with marked seasonality. This pattern is consistent with later end-use modeling (e.g., higher space-heating needs in the Highlands and higher space-cooling needs in the Lowlands).

2.2.2 Data Collection and Processing

Goal: Our sole objective in this section is to build a 2024 dataset with the *number of non-electrified households per municipality.* This is the key input that drives the RAMP demand simulation and the integration into EnergyScope.

Sources and base year: All data come from the Bolivian National Institute of Statistics (INE) [7]. The base year is 2024. When a 2024 municipal variable is not available, we derive it from the most recent municipal census (2012).

Units and regions: Calculations are carried out at the municipal level. Each municipality is assigned to exactly one of the three study regions (Highlands, Lowlands, Valleys); regional totals are simple sums of municipal values.

Step 1: Households per municipality in 2024

Municipal household counts for 2024 are not yet published. We project 2012 household counts using municipal population growth (available for 2024):

$$H_{m,2024} = H_{m,2012} \times \frac{Pop_{m,2024}}{Pop_{m,2012}}.$$

This keeps the method transparent and consistent with official figures.

Step 2: Electrification rate per municipality in 2024

Direct municipal electrification rates for 2024 are also unavailable. We obtain them in three sub-steps, letting $d = d(m)$ denote the department of municipality m:

1. **Departmental target:** From INE departmental series (2011–2023), we project a departmental electrification rate for 2024, $e^{\star}_{d,2024}$, and form a growth factor $G_d = e^{\star}_{d,2024}/e_{d,2012}$.

2. **Municipal uplift.** Each municipality's 2012 rate is scaled by its department's growth: $\widehat{e}_{m,2024} = e_{m,2012} \times G_d$. For municipalities at 0% electrification in 2012, we apply a conservative floor of 30% to avoid freezing them at zero over twelve years. Rates are then truncated to the unit interval $[0, 1]$.

3. **Departmental consistency.** A single growth factor may not reproduce the projected 2024 departmental average exactly. We therefore apply a department-specific multiplier c_d so that the weighted average of municipal rates, taking into account the population of each municipality (giving more weight to larger ones while still reflecting smaller ones), matches $p^{\star}_{d,2024}$ within 2%. This is updated iteratively and re-clipped to $[0, 1]$.

Step 3: Electrified and non-electrified households (final output)

With $H_{m,2024}$ (households per municipality), and the corrected municipal electrification rate $e_{m,2024}$,

$$E_{m,2024} = (H_{m,2024} \times e_{m,2024}), \qquad U_{m,2024} = H_{m,2024} - E_{m,2024}.$$

Here $U_{m,2024}$ is the **number of non-electrified households** per municipality in 2024, i.e., the quantity required by our modeling pipeline. Municipal values are summed to obtain regional totals for Highlands, Lowlands, and Valleys.

Non-electrified households by region

Table 2.1 summarizes the final results of the procedure described above, presenting the estimated number of non-electrified households per region in 2024.

This three-step pipeline yields a clean, 2024-consistent map of non-electrified households by municipality, fully based on INE statistics and ready for modelling.

Table 2.1: Estimated number of non-electrified households per region in 2024

Region	**Non-electrified Households**
Highlands	28.445
Valleys	49.155
Lowlands	56.477

Assumptions

- Households grow proportionally to municipal population (transparent and reproducible).
- Municipal electrification rates inherit departmental growth; a 30% floor avoids locking 2012 zeroes at zero.
- Departmental alignment ensures 2024 municipal data are consistent with official departmental targets (tolerance $< 2\%$).

2.3 RAMP Simulation

2.3.1 Theoretical Framework: The RAMP Model

RAMP is an open-source, Python-based, bottom-up stochastic tool that generates high-resolution energy-demand time series from a minimal set of appliance-level inputs [20]. In this work, RAMP is used to produce realistic minute-resolution electricity demand profiles for rural contexts, which are subsequently aggregated and integrated into the system optimisation framework.

Conceptually, RAMP models each appliance with a small set of parameters—rated power, probability distributions for switch-on events, and operational constraints (e.g., allowable hours, climatic dependencies). These stochastic rules yield diverse, non-repetitive daily patterns that capture user-behaviour variability across days and seasons. Individual appliance profiles are summed at the user level and can be further scaled and aggregated to represent regions.

2.3.2 Scenario Design

The goal of this section is to define and generate electricity demand profiles for currently non-electrified areas in Bolivia. These demand profiles are structured by use case, specifically households, community services, and income-generating activities (IGAs), and are used to produce the demand data required by the EnergyScope Multi-Cell model.

The segmentation by use case allows the model to reflect the different electricity needs observed in rural and isolated communities. Each category presents distinct usage patterns and levels of service, which must be considered independently to build realistic demand estimations. RAMP is used to simulate these different types of demand based on context-specific input data and behavioural patterns.

The demand profiles are created using assumptions related to household characteristics, equipment availability and typical service usage. These assumptions are adapted to the rural Bolivian context.

The following subsections present the methodology and input data used to model each use case individually.

Assumptions and Data Sources

The definition of inputs for household energy demand was based on past works developed in the Bolivian context. Power consumption values for various devices and appliances were primarily obtained from the official RAMP Bolivia GitHub repository [21], which contains validated input sets for rural Bolivian contexts. These values were reviewed and adjusted when necessary to reflect local conditions or updated assumptions.

Energy Sufficiency: It is important to highlight that all demand profiles in this study are modeled under the principle of energy sufficiency. This means that the simulations consider a minimum level of electricity demand, based on the assumption that households in non-electrified areas have a latent energy demand that is currently unsatisfied due to lack of infraestructure and economic constrains. In this sense, although the concept of Energy Sufficiency has been extensively examined from a Global North perspective, a recent study has approached it through a Global South lens, framing it as a normative tool to guide universal access and achieve tangible impact by identifying latent demand in disadvantaged regions [19].

As a result, the selection of appliances and services included in each use case reflects this constraint. For instance, in the case of space cooling, only basic technologies such as electric fans are considered, while more energy-intensive options like air conditioning are excluded. This approach ensures that the model realistically represents basic but essential energy needs, rather than aspirational or luxury consumption patterns.

2.3.3 RAMP inputs

To simulate electricity demand using RAMP, it is necessary to provide input scripts that represent the different elements that may consume electricity in unelectrified areas. These inputs include the quantity of each element, their power consumption, and their usage patterns, which are defined through daily time-of-use windows.

RAMP uses this information to generate stochastic final demand profiles that reflect user behaviour in different rural contexts. For this study, the inputs were structured into three main categories: households, community services, and income generating activities (IGAs). Each category was further differentiated by geographic region, including highlands, valleys, and lowlands, and by season, covering summer, autumn, winter, and spring. This approach allows the model to account for spatial and seasonal variation in energy demand.

Not all inputs vary across regions or seasons. However, specific differences were introduced whenever they were considered relevant to local conditions. For instance, heating needs in highland households during winter are significantly higher than in lowland areas, where such demand is negligible.

The following sections describe the main inputs within each category, explaining how they were defined and how their characteristics change depending on region and season.

Input Structure and Classification: RAMP requires a well-structured set of input definitions in order to simulate electricity demand accurately. These inputs are organized into multiple levels that reflect the geographic, functional, and technical context of rural energy use.

First, inputs are differentiated by geographic region: highlands, lowlands, and valleys. Within each region, inputs are further classified by use case: households, community services, and income-generating activities (IGAs). Each use case includes one or more infrastructure types, which represent distinct energy-consuming units (e.g., a school, a workshop, or a household).

Each infrastructure includes one or more appliances, depending on its function. For example, a typical household input for cooling may include only a single appliance, such as a fan. In contrast, an ICT-related input may include multiple appliances such as mobile phone chargers, radios, or laptops.

This structured classification enables the model to generate demand profiles that are sensitive to both regional characteristics and the diversity of energy uses found in rural communities.

How Inputs Are Modelled: Each RAMP input is defined by first specifying the user, which corresponds to a particular type of infrastructure in a given region. This may include, for example, a school, a health center, or an entertainment business, depending on the use case and geographic area.

Next, the appliances associated with each infrastructure are defined. Appliances represent the individual electricity-consuming devices within each input. As previously mentioned, a single input can contain one or multiple appliances depending on the expected energy services for that infrastructure.

For each appliance, a number of key parameters must be specified:

- **Number of appliances per infrastructure** – e.g., multiple LED bulbs in a single household.
- **Nominal power** – the rated power consumption of each appliance.
- **Number of time windows** – how many periods of use occur during a typical day.

- **Total usage time** – total minutes per day the appliance is in operation.
- **Minimum cycle duration** – the shortest time the appliance stays on once activated.
- **Daily time windows** – time intervals during which the appliance is typically used.
- **Window variability** – random variation applied to start/end times of usage windows.
- **Usage time variability** – random variation applied to total daily usage duration.

An example configuration might look as follows:

```
num windows = 2                # how many usage time windows throughout the day?
func time = 120                # total usage time in minutes
func cycle = 10                # minimum usage time after switch-on
window 1 = [0, 30]             # usage from 00:00 to 00:30
window 2 = [1170, 1440]        # usage from 19:30 to 24:00
random var w = 0.35            # variability of window times (35%)
time fraction random variability = 0.2  # variability of usage duration
```

Once these parameters are defined, the appliance is fully specified within the model.

The following sections provide a brief overview of the main inputs defined for each use case. Due to the large number of inputs modelled in this work, it is not feasible to describe each of them in detail. Instead, the focus is placed on summarizing the most relevant characteristics and modelling assumptions for each type of service.

Households

Household-level electricity demand plays a fundamental role in rural electrification planning. In this study, the modelling of household demand focuses on typical uses of electricity in unelectrified or newly electrified rural areas that are not yet connected to the national grid.

Notably, cooking was not included. The main reason is the difficulty of accurately defining appliance-specific parameters for this end-use, such as peak power, usage frequency, and duration, in rural contexts where electricity is not the primary energy carrier. In addition, no previous work using RAMP in Bolivia has considered cooking, which means that no reliable source of information was available to implement the required inputs.

To illustrate the typical range of power consumption and daily usage patterns for each household-level input, a simulation was conducted for a single representative household. The resulting figure shows the average annual demand profile condensed into a single representative day. It displays a cloud of data points representing all simulated load values for each time step of the day, along with a solid line indicating the average consumption profile.

Modelled inputs

- **Illumination:**
  Lighting was considered an essential use across all households. The model includes two types of lighting: interior and exterior. Interior lighting is assumed to be used primarily during evening and early morning hours, while exterior lighting is limited to shorter periods and represents approximately half the usage time of interior lighting. It was assumed that LED lights are used in all cases.

  Figure 2.3 shows the daily electricity demand profile for the illumination input of a single household. It illustrates both the typical power range and the time-of-day patterns associated with lighting usage.

  Seasonal variation is taken into account to reflect changes in natural daylight. In summer, lighting demand is lower due to extended daylight hours. In contrast, winter profiles assume longer usage durations, especially during mornings and evenings. Autumn and spring represent intermediate cases, and the same pattern is applied to both seasons.

  No regional variation was applied for lighting, as daylight availability is assumed to be consistent across the country.

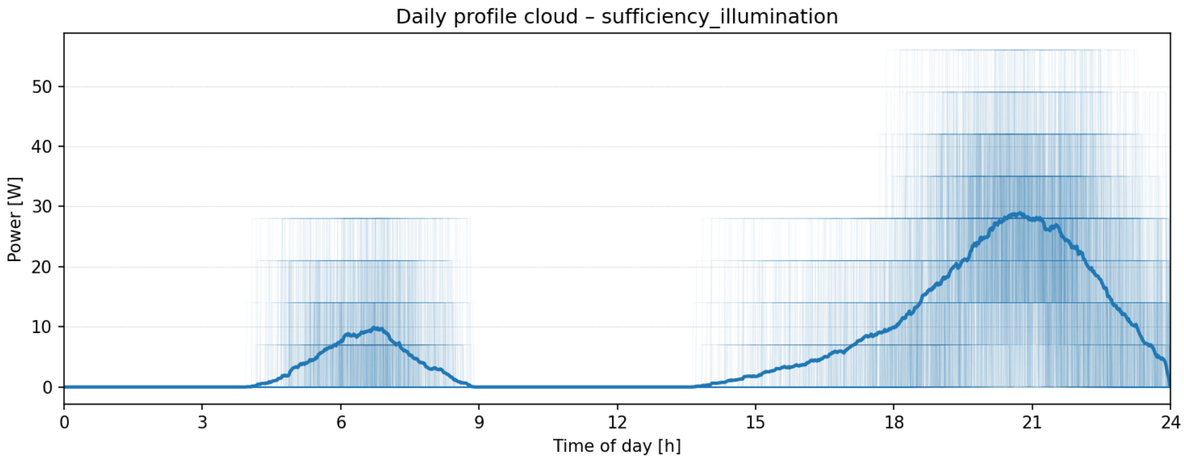

Figure 2.3: Daily illumination demand profile from a household in the Lowlands

- **ICT:**
  Information and communication technology (ICT) devices are included as part of typical household energy use. The model considers one unit of each of the following devices: television, radio, and laptop. Additionally, four mobile phone chargers are assumed per household, reflecting the widespread use of mobile communication even in rural areas.

  No seasonal variation is applied to ICT usage, as it is assumed that consumption remains constant throughout the year. The use of these devices is modelled to occur mainly during evening and night hours, when household occupancy is typically highest. An exception is the radio, which is also used during morning hours.

  Figure 2.4 displays the simulated electricity demand associated with ICT use in a single household. It highlights the characteristic power levels of this input and its contribution to the overall daily consumption pattern.

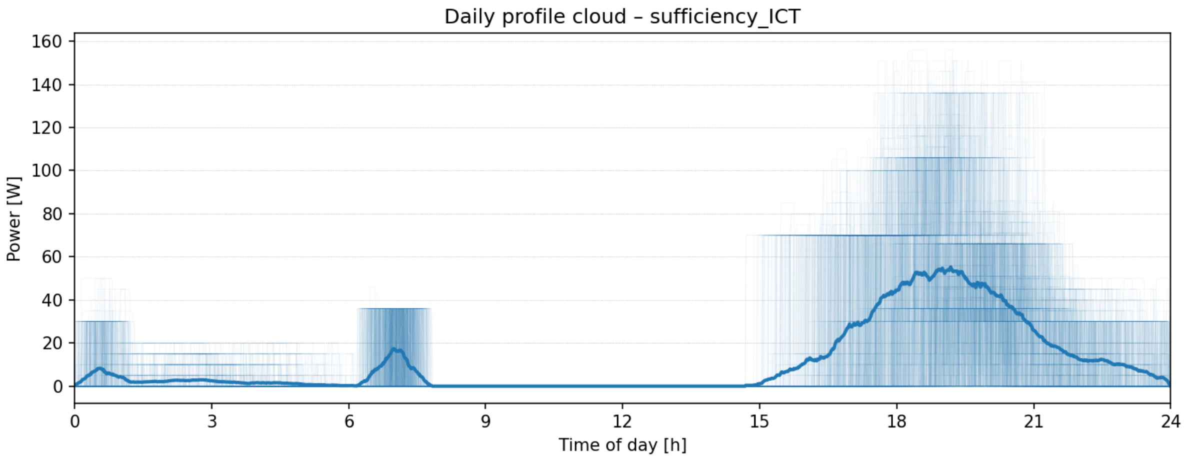

Figure 2.4: Daily ICT demand profile from a household in the Lowlands

- **Cold Storage:**
  Cold storage is included to represent the preservation needs of perishable food and medicine in rural households. In the highlands, where temperatures are generally low, the cold storage demand is assumed to remain constant throughout the year, as there is limited need for additional cooling.

  The same assumption is applied to the valleys, since this region typically experiences mild temperatures and does not require significant refrigeration variation across seasons.

  In contrast, in the lowlands, cooling requirements are higher due to the warmer climate. For this reason, the model applies seasonal variation to the input. Only winter follows the same profile as the other regions, while summer, autumn, and spring are modelled with increased power demand to account for higher ambient temperatures.

  Figure 2.5 shows that the electricity demand for cold storage is notably more constant throughout the day compared to other inputs. It also operates at a significantly higher power level.

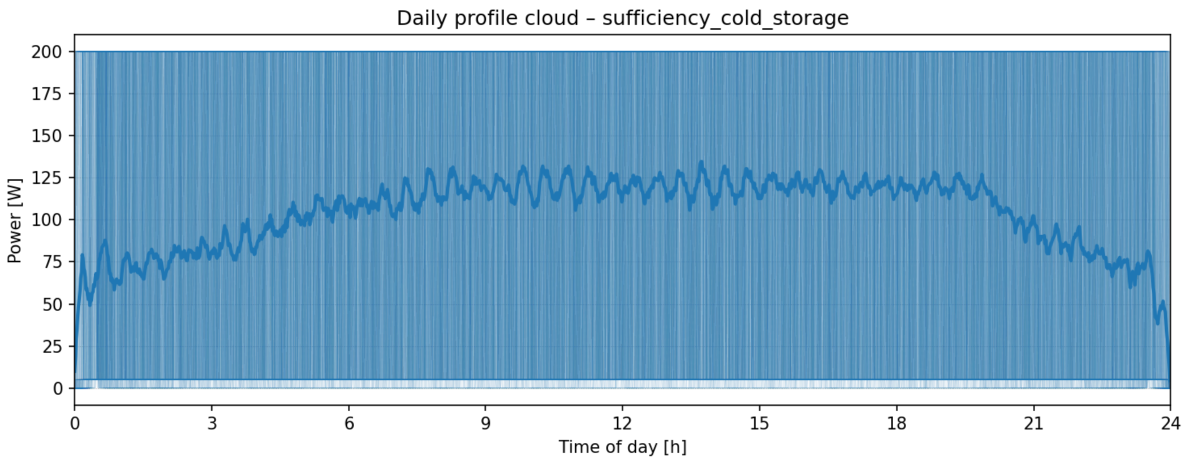

Figure 2.5: Daily cold storage demand profile from a household in the Lowlands

- **Thermal comfort:**
  Thermal comfort includes both heating and cooling needs, which are modelled separately but described under the same category. This approach allows the model to account for thermal behaviour based on the specific climate conditions of each region.

  In the highlands, space heating is considered only during winter, where a heater of 800 W per household is included. For the rest of the year, no thermal comfort devices are assumed, given the relatively cold climate and lack of need for cooling.

  In the lowlands, cooling is considered necessary during summer, spring, and autumn. One fan per household is included for these seasons. No thermal comfort equipment is modelled for winter, as temperatures are assumed to be mild enough. Figure 2.6 presents the simulated electricity demand for thermal comfort in a household located in the lowlands region.

  In the valleys, no thermal comfort devices are considered at any time of the year. The region's moderate climate is assumed to eliminate the need for either heating or cooling in rural households.

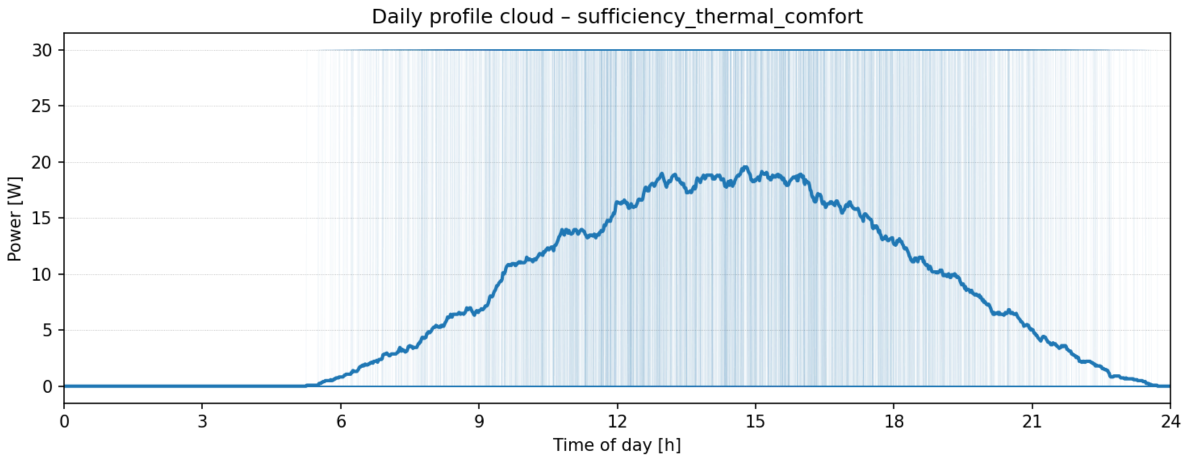

Figure 2.6: Daily thermal comfort demand profile from a household in the Lowlands

- **Water Heating:**
  Water heating demand was modelled using the equations and methodology presented in the study "Modeling of a Village-Scale Multi-Energy System for the Integrated Supply of Electric and Thermal Energy" [22]. This method accounts for seasonal variation in groundwater temperature, which directly affects the energy required to heat water for domestic tasks.

  The first step involves estimating the daily groundwater temperature using the following expression:

$$T_{gw}(n_{day}) = \overline{T_{amb}} - 3\cos\left(\frac{2\pi}{365}\left(n_{day} - n_{day}^{min}\right)\right) \quad [K] \tag{2.2}$$

  where:

  - T_{gw} [K] is the groundwater temperature;

- n_{day} [–] is the progressive number of the considered day of the year;
- $\overline{T_{amb}}$ [K] is the yearly average ambient temperature;
- n_{day}^{min} [–] is the progressive number of the day with the lowest temperature of the year.

This equation generates a time series of daily groundwater temperatures, enabling the model to reflect seasonal differences. Colder periods result in lower groundwater temperatures and, consequently, greater energy needs for heating.

The power required for heating water is then calculated using:

$$P_{task} = \dot{m}_w c_{pw} (T_{task} - T_{gw}) \tag{2.3}$$

where:

- P_{task} [W] is the power required to heat the water for the operation of the task;
- $\dot{m}_w$ $[\mathrm{m}^3/\mathrm{s}]$ is the water mass flow required by the task, fixed to $0,8\,\mathrm{m}^3/\mathrm{s}$;
- c_{pw} $\left[\frac{kJ}{kg\,K}\right]$ is the water isobaric specific heat;
- T_{task} [K] is the temperature of the water needed for the specific task, fixed to 40ºC;
- T_{gw} [K] is the groundwater temperature.

In this study, each household is assumed to perform two hot water tasks per day, corresponding to shower usage. The final power demand varies throughout the year and is consistent with the thermal behaviour determined by the groundwater temperature profile. Figure 2.7 shows the average daily demand profile for water heating. As seen in the cloud of data points, demand fluctuates depending on the season—requiring higher power levels during colder days, particularly in winter, and lower levels during warmer periods.

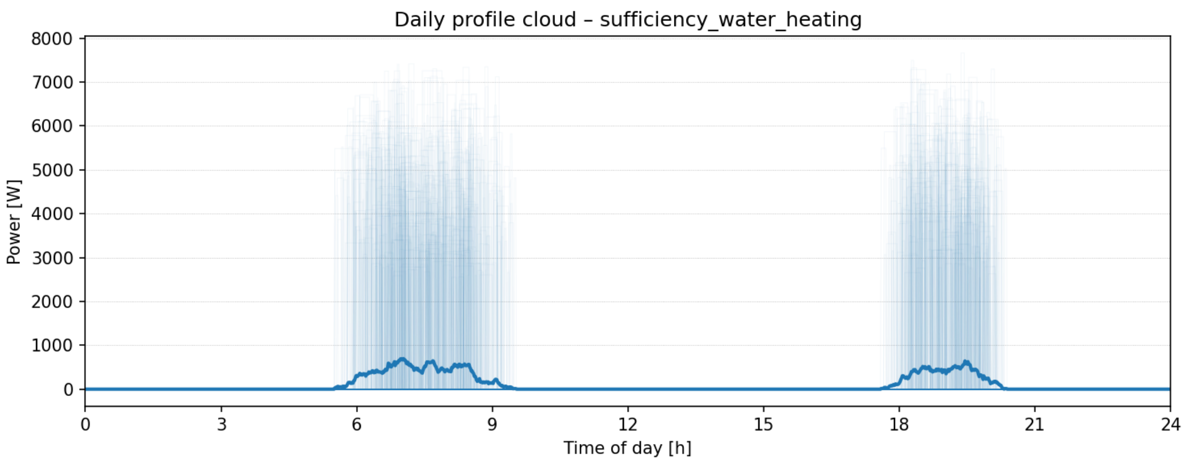

Figure 2.7: Daily water heating demand profile from a household in the Highlands

Community Services

Community services represent essential infrastructure that supports basic social, educational, and health-related functions within rural communities.

In this study, electricity demand from community services is modelled separately from household demand in order to reflect their distinct usage patterns and power requirements. The selection of services is based on typical public facilities found in small Bolivian communities, such as schools, health centers and public lighting.

Each service is composed of several inputs, which are modelled similarly to those described in the previous section. These inputs are adapted to reflect the specific needs of each service. In some cases, input characteristics may vary depending on the region or the season of the year.

The following subsections describe each service individually, detailing the input assumptions used in the model.

Service Types:

Health Centers

Health centers are a critical component of rural infrastructure, providing essential medical services and contributing directly to the well-being of isolated populations. Electrification of these facilities enables the operation of lighting, refrigeration for vaccines and medicines, basic medical equipment, and communication technologies. In this study, the electricity demand of rural health centers in Bolivia is defined according to the typical services they provide and the appliances commonly used in these contexts. These centers are considered a priority in rural electrification efforts due to their direct impact on public health.

- **Illumination:**
  Lighting is one of the fundamental energy needs in rural health centers, ensuring the safe delivery of medical services during both day and night. All facilities are assumed to require continuous illumination in key areas such as consultation rooms, patient observation zones, storage areas for medical supplies, and administrative offices. Given that these are fully enclosed buildings with limited reliance on natural light, lighting demand is considered stable throughout the year, without seasonal or regional differentiation. The model assumes the use of LED bulbs due to their high energy efficiency and increasing adoption in rural electrification projects.
- **ICT:**
  Health centers require basic communication and information technologies to support administrative activities, coordination with external institutions, and access to medical information. The appliances considered in this category include mobile phone chargers, televisions, radios, computers, and printers. These devices enable essential functions such as patient record management or telecommunication with regional health authorities. Given the modest size of the facilities under consideration, the presence of two units per device has been assumed. No variation across geographic regions or seasons has been introduced, as the ICT-related demand is expected to remain consistent throughout the year and across different contexts.

- **Cold Storage:**
  Refrigeration is essential in health centers to guarantee the preservation of vaccines, medicines, and other temperature-sensitive supplies. The associated electricity demand is considered constant in all regions and during all seasons. Although there are climatic differences across Bolivia, they are not expected to significantly affect the operation of medical refrigerators in these facilities. For this reason, no variation in cold storage demand is introduced in the model.
- **Space Cooling:**
  Space cooling is only considered necessary in the lowlands region, where high temperatures and humidity levels make thermal comfort a relevant factor. In these areas, the use of electric fans is assumed during all seasons except winter. In the highlands and valleys, no space cooling is included in the model, as ambient temperatures remain moderate or low throughout the year, making artificial cooling unnecessary.
- **Medical Equipment:**
  Rural health centers are expected to include a minimum set of medical devices to carry out basic diagnostic and treatment procedures. The appliances considered in this category are: sterilizer stove, needle destroyer, microscope, dental compressor, centrifuge, and serological rotator. These devices were selected based on the configuration used by the RAMP Bolivia team in previous rural electrification projects [12], relying on their expert knowledge of the Bolivian healthcare context. No variation by region or season is introduced in this category, as the presence and use of these devices is assumed to be standard across all health centers modeled.
- **Water Heating:**
  This component is modeled following the same assumptions and methodology as described in Section 3.8.1: Water Heating. However, in the case of health centers, water heating is assumed to be less frequent and with lower daily usage compared to households. This is because hot water is used mainly for hygiene-related tasks such as hand washing and cleaning instruments, rather than for regular personal use like bathing or cooking.
- **Water Supply:**
  The energy consumption associated with water supply has been included in the model, as it is considered relevant for the operation of rural health centers. This demand accounts for the use of an electric water pump to ensure access to clean water for sanitation and basic medical needs. One water pump per health center is assumed. No seasonal or regional variation is introduced, as the basic water requirements of health centers are expected to remain consistent throughout the year.
- **Space Heating:**
  Space heating is considered necessary during the winter months in the highlands region, which is the coldest area of the country. Although temperatures are not extreme, the climate is sufficiently cool during this period to justify the inclusion of heating in health centers. No space heating is modeled for the valleys or lowlands, where winter conditions do not require it.

Schools

In this study, schools are modelled as large educational buildings with the capacity to host a high number of students.

- **Illumination:**
  A standard lighting profile is considered for all regions and seasons. The school is assumed to operate during daytime hours, with lighting required in all classrooms and administrative areas. The use of LED light bulbs is assumed throughout the facility. No variation is introduced across regions, as indoor lighting needs remain constant regardless of local conditions.
- **ICT:**
  The ICT-related demand includes television, radio, DVD player, computer, mobile phone chargers, printers, stereo system and data-related equipment such as Wi-Fi connection devices. A fixed number of units is considered for each school, with no variation across regions or seasons. These appliances are included to cover basic communication, administrative, and student-related needs in rural educational facilities.
- **Cold Storage:**
  Due to the warmer climate in the Lowlands, a higher cooling capacity is considered for this region. In the Highlands and Valleys, where ambient temperatures are generally lower, a more conservative value is assumed.
- **Space Heating:**
  In the Highlands, space heating is considered during the winter period only. A heater is assumed to be used in classrooms and administrative areas to provide minimal thermal comfort during colder months. In the Lowlands and Valleys, no space heating is included, as temperatures are generally higher.
- **Space Cooling:** Space cooling is considered in the Lowlands region for all months except winter. A fan is assumed to be used in classrooms and administrative areas to reduce indoor discomfort during warmer periods. No cooling is included in the Highlands or Valleys.

Public Lighting

Public lighting contributes to safety and accessibility in rural communities during evening and nighttime hours. It is considered an important service for common areas such as streets and village centers.

- **Illumination:**
  Lighting inputs are assumed to remain constant throughout the year and across all regions. Although daylight duration varies between seasons, especially between summer and winter, these changes are not considered significant enough to justify differentiated modeling.

Income Generating Activities (IGAs)

Income generating activities are an essential part of rural life and play a key role in improving the economic sustainability of isolated communities. In the context of rural electrification, these activities represent productive uses of electricity that go beyond basic household and community needs. Their inclusion in the model allows for a more accurate representation of total demand and reflects the development opportunities that electrification can unlock. In this study, IGAs are categorized according to typical practices observed in Bolivian rural areas.

Service types:

Entretainment business
This category represents small local businesses, these businesses play a relevant role in the social dynamics of rural communities, providing meeting points and contributing to local economic activity. The business is modeled with a basic set of appliances typically found in such contexts, as detailed below.

- **Illumination:**
  The simulated business includes basic lighting, which is assumed to remain constant throughout the year and across all regions. Although daylight duration may vary slightly between seasons, these differences are not considered significant for this type of use.
- **ICT:**
  The electronic devices considered for this business are a stereo system, a television, and a computer. As it is modeled as a small-scale business, only one unit of each device is included. The usage of these appliances is assumed to be the same across all regions and seasons.
- **Cold Storage:**
  As the entertainment business is modeled as a small-scale commercial activity, refrigeration demand is assumed to be limited and relatively stable. Although there are climatic differences across regions and seasons in Bolivia, these variations are not considered significant enough to affect the cold storage needs of this type of business. For this reason, the same input is used uniformly across all regions and throughout the year.

Restaurant
This category represents small rural restaurants that operate on a local scale and serve prepared meals or beverages to the community. These establishments are often family-run and form part of the informal economy, providing both an income source and a social space within the village. The business is modeled with a basic set of appliances typically found in these contexts, considering a simplified and consistent configuration across regions and seasons.

- **Illumination:**
  Lighting is modeled in the same way as in other activities, with constant usage assumed throughout the year and across all regions. No seasonal or geographic variation is introduced for this input.
- **Kitchen:**
  The only electric kitchen appliance considered in this case is a blender. As mentioned in the Households section, cooking demands are not modelled with RAMP.
- **Cold Storage:**
  As in previous cases, cold storage is included as a necessary component for this

type of business. The presence of a refrigeration appliance is considered essential for preserving food and beverages. No variation by region or season is introduced.

Store

This category represents a small rural store that sells basic goods such as packaged food, beverages, and household items. These establishments are usually family-operated and serve as an important commercial node within the community, often being the main access point to consumer products. The business is modeled with a minimal set of electric appliances, based on typical equipment found in similar contexts.

- **Illumination:**
  Lighting is modeled in the same way as for the other activities, with constant use assumed throughout the year and across all regions.
- **ICT:**
  Only a radio is considered under this category, as no additional electronic devices are expected to be used in a small rural store. This reflects the limited ICT needs typically observed in this type of establishment.
- **Cold Storage:**
  As in the other activities, cold storage is included as a necessary element to preserve perishable products such as beverages or packaged food. The same input is applied across all regions and seasons, without variation.

Workshop

The workshop is modelled as a multi-purpose facility intended for various technical and mechanical tasks in rural areas. It is assumed to operate on a daily basis during standard working hours. The configuration reflects small-scale environments where different tools and machinery are used depending on the type of work carried out. The electricity demand considers a simplified setup based on selected equipment with significant power needs, representative of typical rural workshops.

- **Illumination:**
  A standard lighting profile is assumed for all regions and seasons. The workshop is expected to operate indoors during working hours, and lighting is considered necessary in all areas of activity.
- **ICT:**
  ICT-related demand is limited to a single radio unit. No additional devices are considered, as communication needs in the workshop are assumed to be minimal.
- **Machinery:**
  The workshop includes a welding machine and a grinding machine. Both appliances have high power requirements and have been modelled accordingly. Their usage is concentrated during working hours and reflects typical mechanical tasks carried out in small rural workshops.

Flour Procesing:

In the Lowlands, flour processing is considered as a local activity involving the transformation of grains into flour. The modelling includes a grain dryer, a grain miller, and a grain toaster, representing the typical stages of drying, grinding, and final treatment of the product. A water pump is also included to supply the necessary water for the process. These appliances operate with moderate to high power demand and are assumed to follow a daily usage schedule. The configuration reflects common practices in rural areas where flour is produced for local use.

Quinoa Processing:
In the Highlands, quinoa processing is included as a typical local activity. The process involves several steps, represented in the model by a quinoa washing machine, a grain dryer, a grain miller, and a grain toaster. These appliances cover the full cycle from cleaning to drying, milling, and toasting. The equipment has high power requirements and is assumed to operate according to a regular working-day schedule. The configuration reflects small-scale facilities commonly found in quinoa-producing communities.

Milk Production:
Milk production is only considered in the Valleys region, where dairy farming is assumed to be more common than in other areas. The model includes a cooler tank with high power demand and a milking machine, representing the key equipment used in small-scale rural dairy production. The appliances are assumed to operate on a regular basis following a daily schedule.

Regional Summary of RAMP Inputs

To conclude the specification of RAMP inputs, Table 2.2 summarises the *regional* differences considered across Highlands (HL), Valleys (V), and Lowlands (LL). The table reports only what changes by region.
Convention. A dash (—) in a region column indicates that the input is modelled uniformly across regions (i.e., no regional differences). Cells contain text only where a region-specific configuration deviates. Seasonal effects do not imply regional differences.

Input / Sector	Highlands (HL)	Valleys (V)	Lowlands (LL)
Households			
Lighting	—	—	—
ICT	—	—	—
Cold storage	—	—	Higher and seasonal (except winter)
Thermal comfort	Space heating (winter only)	None	Fans (cooling) except winter
Water heating (ACS)	Higher needs	Moderate–high	Lower needs
Community Services — Health centers			
Lighting / ICT	—	—	—
Cold storage (vaccines/medicines)	—	—	—
Water supply (pumping)	—	—	—
Medical equipment	—	—	—
Thermal comfort	Space heating (winter only)	None	Fans (cooling) except winter
Community Services — Schools			
Lighting / ICT	—	—	—
Cold storage	—	—	Higher capacity
Space heating / cooling	Space heating (winter only)	None	Fans (cooling) except winter
Public lighting			
Illumination	—	—	—
IGAs (Income-Generating Activities)			
Common small businesses (store, restaurant, workshop, entertainment)	—	—	—
Region-specific IGA	Quinoa processing	Milk production	Flour processing

Table 2.2: Summary of regional differences in RAMP inputs.

2.3.4 Quantification of Infrastructure

Once the types of energy-consuming infrastructures have been defined, it is essential to determine their quantity in order to ensure that the resulting electricity demand reflects the reality of non-electrified rural areas as accurately as possible. In this context, each input unit is designed to represent one actual instance of the corresponding infrastructure. For example, one input unit of health center refers to a single functioning health center.

The infrastructure counts used in this study are based on the methodology presented in Electricity demand forecasting for rural communities in developing countries: Calibrating a stochastic model for the Bolivian case (2023) [12]. This work provides a detailed breakdown of each infrastructure category, such as health centers, workshops, schools, restaurants, and stores, along with the corresponding data sources used to justify the proposed values. For the purpose of this thesis, some of the original figures have been slightly adapted to better reflect the specific characteristics of the case analysed here. Notably, the cited study also makes use of the same geographical classification used in this work, distinguishing between Highlands, Valleys, and Lowlands. This alignment makes the criteria especially useful and directly applicable to our modelling approach.

Based on the referenced work, we obtain the infrastructure allocation criteria shown in Table 2.3, which establish the number of infrastructure units per number of households (HH) or inhabitants.

Table 2.3: Criteria for the allocation of (a) community services infrastructure and (b) IGAs in rural communities according to the population size of the communities

(a) Community services infrastructure

Infrastructure	**Criteria**
1 Health center	for each 5000 inhab.
1 Public lighting post	per every 10 HH
1 School	for each 5000 inhab.

(b) IGAs in rural communities

Activity	**HL**	**VA**	**LL**
1 Quinoa processing	200HH	-	-
1 Flour processing	-	-	200HH
1 Milk production	-	200HH	-
1 Store	25HH	25HH	30HH
1 Restaurant	30HH	30HH	30HH
1 Workshop	80HH	70HH	60HH
1 Entertainment business	100HH	80HH	60HH

As shown, certain infrastructures are calculated based on the number of households, while others rely on the number of inhabitants living in those households. However, detailed population figures for non-electrified communities are not directly available. Therefore, an average household size of 3,14 inhabitants is assumed, based on the most recent data provided by Bolivia's National Institute of Statistics (INE) [7]. Using this average, and the number of households in each region, as shown in Table 2.1 we estimate the total number of inhabitants, as shown in Table 2.4.

Finally, by applying the criteria from Table 2.3 to the regional figures from Table 2.4, we obtain the resulting number of infrastructure units per region, shown in Table 2.5.

With the infrastructure types defined and their quantities estimated per region, all the necessary information is now available to model the corresponding energy inputs in RAMP. Based on these inputs, the tool simulates the electricity demand in non-electrified areas by assigning typical consumption patterns to each infrastructure type. This process

Table 2.4: Number of unelectrified households and inhabitants per region

Infrastructure per region		
Region	**Unelectrified Households**	**Inhabitants**
Highlands	28.445	89.317
Valleys	49.155	154.347
Lowlands	56.477	177.338

Table 2.5: Number of infrastructures per region

Infrastructure per region			
Activity	**HL**	**VA**	**LL**
Households	28.445	49.155	56.477
Health Center	18	31	35
Public Lighting Post	8.932	12.435	17.734
School	18	31	35
Flour processing	142	0	282
Milk production	0	246	0
Store	1.138	1.966	1.883
Restaurant	948	1.639	1.883
Workshop	356	702	941
Entertainment business	284	614	941

allows us to obtain a representative electricity demand profile for each of the three rural regions: Highlands, Valleys, and Lowlands.

2.4 EnergyScope: Formulation and Inputs

2.4.1 Theoretical Framework

EnergyScope Multicell

This section introduces the functioning of the *EnergyScope Multicell* (ES-MC) model, outlining its internal logic, required inputs, and the type of results it generates. ES-MC extends the original EnergyScope framework to a multi-regional structure in which each cell (region) can operate independently or exchange energy carriers with the others.

Problem statement: EnergyScope is formulated as a linear optimization problem whose objective is to minimize the *total annual cost* of the energy system. Let REG denote the set of regions. The objective function reads:

$$\min_{r \in \text{REG}} \sum C_{\text{tot}}(r) \tag{2.4}$$

where $C_{\text{tot}}(r)$ is the total annual system cost in region r.

The total cost decomposes into annualized investment, operation & maintenance, and resource operating costs:

$$C_{\text{tot}}(r) = \sum_{j \in \text{TECH}} \left(\tau(r,j)\, C_{\text{inv}}(r,j) + C_{\text{maint}}(r,j)\right) + \sum_{i \in \text{RES}} C_{\text{op}}(r,i). \tag{2.5}$$

Here, TECH and RES are the sets of technologies and resources, respectively. The annuity factor $\tau(r, j)$ annualizes the investment of technology j in region r based on the discount rate and lifetime; the investment and O&M terms are

$$C_{\text{inv}}(r,j) = c_{\text{inv}}(r,j)\, F(r,j), \qquad C_{\text{maint}}(r,j) = c_{\text{maint}}(r,j)\, F(r,j),$$

with c_{inv} the specific investment cost, c_{maint} the specific O&M cost, and $F(r, j)$ the installed capacity (or energy capacity for storage) of technology j. The resource operating cost $C_{\text{op}}(r, i)$ aggregates the use of local and external resources (e.g., fuels), valued at their corresponding unit costs.

Hourly balance of layers: EnergyScope adopts an end-use demand (EUD) approach with an hourly resolution (indexed by h) over a set of typical days (indexed by td). For each region r and carrier layer $l \in L$ (e.g., Electricity, Heat), the model enforces an energy balance:

$$\begin{aligned}
&\sum_{i \in \text{RES}} f(i,l)\big(R_{t,\text{local}}(r,i,h,td) + R_{t,\text{ext}}(r,i,h,td) + R_{t,\text{imp}}(r,i,h,td) - R_{t,\text{exp}}(r,i,h,td)\big) \\
&+ \sum_{j \in \text{TECH} \setminus \text{STO}} f(j,l)\, F_t(r,j,h,td) \\
&\quad + \sum_{k \in \text{STO}} \left(Sto_{\text{out}}(r,k,l,h,td) - Sto_{\text{in}}(r,k,l,h,td)\right) \\
&\qquad = \text{EndUses}(r,l,h,td).
\end{aligned} \tag{2.6}$$

In (2.6), $f(\cdot, l)$ are the layer incidence coefficients (negative for inputs, positive for outputs), $R_{t,\text{local}}$ and $R_{t,\text{ext}}$ are the hourly uses of local and external (out-of-system) resources, and $R_{t,\text{imp}}/R_{t,\text{exp}}$ are interregional imports/exports among ES-MC cells. The term $F_t(r, j, h, td)$ is the hourly operation of technology j (constrained by installed capacity and availability), while $Sto_{\text{in}}/Sto_{\text{out}}$ denote storage charging/discharging flows. $\text{EndUses}(r, l, h, td)$ represents the hourly end-use demand for layer l in region r, provided as an input to the model.

Notation (sets, indices, and main variables):

$r \in REG$	Regions (cells) of the multicell model.
$j \in TECH$	Technologies; STO $\subset$ TECH are storage technologies.
$i \in RES$	Resources (e.g., fuels).
$l \in L$	Carrier layers (electricity, heat, . . .).
h, td	Hour within typical day td.
$\mathbf{C_{tot}}$	Total annual cost [M€/y].

τ	Annuity factor (from discount rate and lifetime) [y^{-1}].
F, F_t	Installed capacity and hourly operation of technologies [GW]/[GW].
$R_{t,\{\cdot\}}$	Hourly resource use: local, external, imports/exports [GW].
$Sto_{\mathbf{in}}, Sto_{\mathbf{out}}$	Storage charge/discharge flows [GW]; storage state tracked hourly.
$f(\cdot, l)$	Layer mapping coefficients (negative for inputs, positive for outputs).
$EndUses$	Hourly end-use demands per layer and region [GW].

Model scope and exchanges: Demands must be met, for each region and hour, by a combination of locally produced energy, interregional trade (imports/exports among cells), storage operation, and, when allowed, external fuel imports that represent exchanges with countries outside the modeled system.

Equations (2.4)–(2.6) summarize the core optimization logic; the full formulation additionally includes constraints on technology availability, capacity factors and curtailment, storage dynamics, emissions, and resource limits. The complete mathematical development and applications are detailed in the PhD thesis by Thiran [23].

Outputs and required inputs: The goal of EnergyScope is to identify the cost-optimal portfolio of technologies and resources that satisfies regional energy demands. The model returns, among others, installed capacities by technology, energy production and consumption by carrier, hourly operation profiles, and disaggregated costs (M€).

To perform such simulations, the model requires three main sets of inputs:

- Hourly end-use demand profiles for each region and energy carrier.
- A detailed technology database including cost, efficiency, and emissions.
- Availability of local and imported energy resources.

All input data must be specified independently for each region, enabling the model to reflect spatial heterogeneity in demand, supply, and infrastructure development.

EnergyScope Bolivia

For the case of Bolivia, an open-source implementation of the national energy system using EnergyScope Multicell is available through the public GitHub repository *EnergyScope Multicell BO* [16]. This version of the model includes the main interconnected zones of the Bolivian grid: the National Interconnected System (SIN) and the Isolated Systems (SA), based on official data and previously validated configurations.

Additionally, the work titled *Towards a Sustainable Bolivian Energy System in 2050: The Pathway for Decarbonization Under High Renewable Potential* [15] provides a comprehensive reference for techno-economic data regarding Bolivia's energy technologies. This includes investment costs and operational costs which are directly used in this thesis.

Therefore, the simulation framework used in this thesis builds upon the structure of the EnergyScope Multicell BO repository. On top of the base scenario, additional regions representing currently unelectrified areas are progressively integrated, enabling their inclusion in national energy planning and decarbonization pathways.

To establish a baseline for comparison, it is first necessary to analyze the behavior of the current model setup, without the added unelectrified zones. This reference simulation represents the current status of Bolivia's main regions (SIN and SA) and is used as the benchmark to evaluate the impact of expanding electrification coverage. It must be noted that electric grid costs and mobility-related energy use are excluded from this simulation.

Energy mix and system overview (2024 scenario)

The following figures show the breakdown of installed electricity generation capacity and energy produced throughout the year in the base scenario, as it is in the GitHub repository [16]:

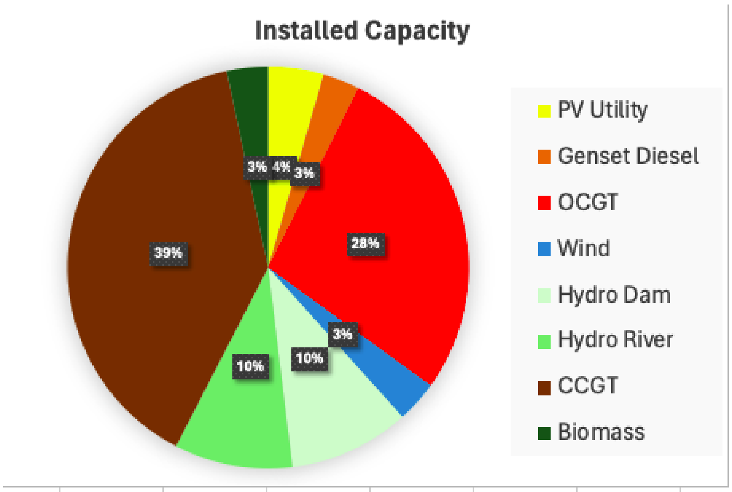

Figure 2.8: Installed generation capacity mix – Base scenario (2024)

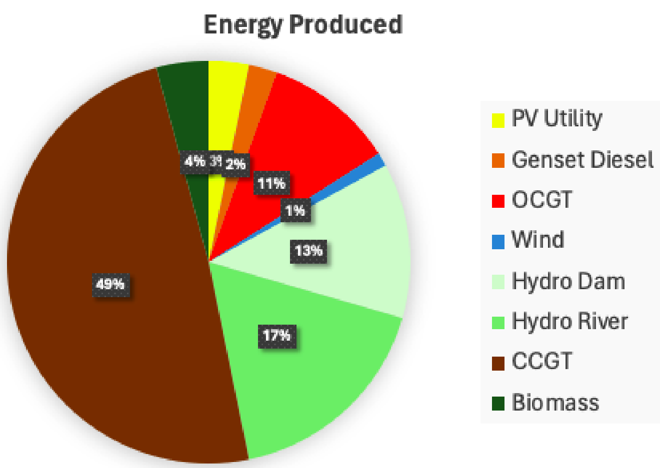

Figure 2.9: Electricity production mix – Base scenario (2024)

As shown in Figure 2.8, the installed capacity is largely dominated by gas-based technologies, which account for approximately **67%** of the total, this includes both Open Cycle Gas Turbines (OCGT) and Combined Cycle Gas Turbines (CCGT). Hydropower technologies also play a significant role, contributing a combined **20%** of the total installed capacity. In contrast, solar and wind technologies represent a relatively small share, together amounting to around **7%**. Biomass and diesel each contribute approximately **3%** of the installed capacity.

In Figure 2.9, the distribution of actual electricity production shows a shift in relative contributions. Combined Cycle Gas Turbines gain even greater relevance, accounting for nearly **50%** of the total energy generated. Hydropower technologies follow, together supplying roughly **30%** of annual electricity generation. Meanwhile, technologies such as solar PV and wind contribute marginally to the energy mix despite their installed capacity, indicating lower capacity factors or limited utilization.

Key numerical results – 2024 base scenario

- **Total installed capacity:** 3,82 GW
- **Annual energy produced:** 10.881,55 GWh
- **Annual system cost:** 805,6 million euros
- **Annual CO_2 emissions:** 19.403,12 tonnes
- **Installed battery storage:** 0,493 MW

This base simulation provides insights into the current mix of energy generation technologies, associated costs, and greenhouse gas emissions.

These figures provide a comprehensive snapshot of the current state of Bolivia's centralized energy system, and they will serve as a reference point for evaluating the incremental impacts of integrating unelectrified areas and decentralized technologies.

Complementary technologies

Although not directly involved in electricity generation, several auxiliary technologies are included in the simulation to reflect realistic energy service provision. The most relevant for our study include:

- Diesel and biomass storage systems
- LED-based lighting
- Decentralized water heating technologies

2.4.2 Assumptions of our Simulation

In order to address the rural electrification in Bolivia it is necessary to clarify the key assumptions made to simplify and adapt the model to the new context.

Modeling of New Regions

As described in previous sections, this study introduces three new regions, the Highlands, Lowlands, and Valleys, which represent areas currently not covered by the national electricity network (neither the SIN nor the SA systems). These regions comprise dispersed, rural communities with no existing grid connection, and therefore require dedicated electrification strategies.

In this simulation, each of the three new regions is modeled as an isolated cell, meaning there is no energy exchange with the existing national system or between the new regions themselves. This assumption reflects the physical and economic difficulty of extending the transmission grid to remote areas and is aligned with decentralized electrification approaches.

Furthermore, all unelectrified demand within each region is aggregated into a single representative demand block. In other words, the Highlands, Lowlands, and Valleys are each modeled as one synthetic zone, without considering internal spatial separation between communities. This simplification allows the model to remain computationally tractable and is justified by the limited availability of high-resolution spatial data, as well as by the high computational cost of adding more cells to the EnergyScope Multicell model.

While this approach does not allow for detailed microgrid layout design or optimization, it is considered sufficient to estimate the technological composition and investment required to electrify these regions under least-cost conditions.

No Interactions Between New and Existing Cells

Due to the rural and isolated nature of the newly introduced regions, they are assumed to operate independently in terms of energy exchange. There are no electricity flows between the new cells (Highlands, Lowlands, Valleys) and the existing SIN or SA zones, nor between the new cells themselves. However, the model allows for unidirectional resource flows: the new regions can import energy carriers such as diesel or natural gas from other parts of the system. This limited interaction reflects realistic logistical conditions, where fuel supply chains may reach remote communities, even if these areas are not physically connected to the national electricity grid. This assumption both simplifies the optimization and maintains a feasible planning approach for decentralized electrification.

Exclusion of Transport and Network Costs

In the standard EnergyScope Multicell BO repository, transport energy demand (both for passengers and freight) is included. However, in this study, transport is excluded from the scope. Modeling transport in highly rural and fragmented regions would require detailed knowledge of distances, mobility patterns, and infrastructure, data that is currently not available for the unelectrified communities considered.

Similarly, electricity network costs are excluded for the new regions. Including such costs would introduce a bias when comparing centralized grid-connected areas with decentralized and isolated communities. Since the study focuses on energy supply options rather than infrastructure development pathways, grid expansion and reinforcement costs are not considered.

Scenario Definition: Business as Usual

The scenario modeled corresponds to a Business-as-Usual (BAU) configuration, which is used as a reference point for evaluating electrification strategies. This scenario assumes that no significant technological breakthroughs occur over the simulation horizon. It excludes advanced technologies such as synthetic fuels, hydrogen production, or carbon capture and storage (CCS). Instead, it relies on conventional and commercially available technologies, and assumes that energy carriers and consumption patterns evolve following historical trends. This conservative approach provides a realistic benchmark for analyzing electrification under current technology and policy conditions.

2.4.3 Our Simulation Strategy

As introduced in the previous section, the EnergyScope simulation conducted in this thesis follows a Business-as-Usual (BAU) scenario. The main objective is to evaluate how the energy demand of currently unelectrified regions in Bolivia can be met using the most cost-effective technology mix, under existing technological and policy conditions. By doing so, the simulation helps identify feasible electrification pathways for remote areas and addresses the persistent challenge of energy exclusion.

Simulation Years and Snapshot Approach

The simulation is performed for three different target years: 2024, 2035, and 2050. This allows us to capture the potential evolution of Bolivia's rural energy system across short-, medium-, and long-term horizons.

To achieve this, a *snapshot* approach is adopted. This means that each simulation year is treated as an independent optimization problem, where only the technologies that are still within their technical lifetime are considered as inherited from previous stages. All technologies modeled in this study have a technical lifetime exceeding 11 years (as referenced in the EnergyScope Bolivia dataset [16]), which allows for a structured transition of capacities:

- For the year **2024**, all installed capacities are assumed to be new.
- For the year **2035**, the model is constrained such that installed capacity for each technology must be at least as high as in 2024. This reflects technology persistence due to their operational lifetime.
- For the year **2050**, only the technologies installed as new in 2035 are required to remain. Technologies from 2024 are assumed to be decommissioned by then, due to reaching end-of-life.

This logic enables a realistic and phased energy system development pathway, where infrastructure is preserved as long as its lifespan allows, without artificially locking the system to outdated technologies.

2.4.4 EnergyScope Model Inputs

The following subsections group the inputs considered by EnergyScope to perform the simulations. This section addresses the main data categories required by the model, including Demands, Resources, Technologies, Time Series, and Costs. Each category describes the specific information provided, its processing, and its role in defining the conditions under which the optimisation is carried out.

Demands

The RAMP tool generates high-resolution electricity demand profiles by simulating energy consumption based on appliance usage under full electrification assumptions. In this work, such profiles are created by modeling an electrified household or infrastructure, where all end-uses are served with electricity. However, the EnergyScope model requires disaggregated final energy demands per energy service, such as heating, cooling, lighting, or mechanical energy, independently of the energy vector used to supply them.

Therefore, an essential step in the data integration process is the conversion of RAMP's electricity-based output into useful energy demands per end-use category.

This conversion is performed using standard end-use efficiency coefficients embedded in the EnergyScope Multicell Bolivia codebase [16]. These coefficients define the ratio between input electrical energy and the actual useful energy delivered, depending on the appliance or service in question.

For example, EnergyScope defines different conversion efficiencies for lighting depending on the technology used. In this work, all lighting is assumed to be provided by LED technology, which has a high conversion efficiency. The same principle applies to other demand types: for each RAMP-modeled service, the appropriate efficiency value is used when converting the electrical demand to useful energy demand.

The conversion factors applied in this work are summarized as follows:

- 1 unit of electricity = 0.34 units of useful lighting (LEDs)
- 1 unit of electricity = 1.00 unit of useful thermal energy (hot water and space heating), assuming resistive heaters with negligible losses
- 1 unit of electricity = 0.35813 units of useful cold energy (food preservation / refrigeration)
- 1 unit of electricity = 0.90 units of useful mechanical energy (industrial and agricultural)
- 1 unit of electricity = 0.80 units of useful cooling (fans)

These values are directly applied within the EnergyScope model to translate electricity demand into useful energy requirements per category.

Other minor demands that are not covered by specific conversion factors are treated as purely electrical end-uses and directly included in the model without conversion. These account for a very small portion of total energy consumption and are therefore assumed to have negligible impact on the optimization outcome.

Cooking Demands

Cooking demand is treated as a separate category in this work, since it was not modeled using RAMP, as explained in Section 2.3.3. The main reasons are the difficulty of defining appliance-specific parameters for cooking, the fact that no previous work using RAMP in Bolivia has included cooking, and the lack of reliable data to implement the required inputs.

Cooking is modeled as a thermal energy demand, allowing EnergyScope to determine the most appropriate energy carrier for supplying this service, whether it be biomass, gas, or electricity.

To estimate total cooking demand, a distinction is made between two major sources of consumption: restaurants and households.

Cooking Demand from Restaurants

The total annual cooking energy demand from restaurants in Bolivia is reported to be 304.905 GWh, according to data provided by Jimenez Zabalaga et al. [15].

To disaggregate this national value, the number of registered restaurants in Bolivia is used, reported to be 7.746 establishments [24]. Assuming uniform energy use across all restaurants, including those in rural areas, the average thermal cooking demand per restaurant is calculated as:

$$\text{Average demand per restaurant} = \frac{304,905\ \text{GWh}}{7.746} = 0,039363\ \text{GWh/year}$$

Using this figure and the estimated number of restaurants per region treated in section 2.3.4, the cooking energy demand for restaurants in each of the three study regions is computed as:

- **Highlands:** 948 restaurants → 37,32 GWh/year
- **Lowlands:** 1.639 restaurants → 64,52 GWh/year
- **Valleys:** 1.883 restaurants → 74,12 GWh/year

Cooking Demand from Households

For the household sector, thermal cooking demand is estimated based on regional averages provided through expert consultation, specifically by the co-supervisor of this thesis, Pablo Jimenez Zabalaga. The national average thermal energy consumption per unelectrified household is estimated at 0.001344023 GWh/year.

By applying this average to the number of unelectrified households in each region, seen in section 2.3.4 the total household cooking demand is calculated as follows:

- **Highlands:** 28.445 households → 38,23 GWh/year
- **Lowlands:** 56.477 households → 75,91 GWh/year
- **Valleys:** 49.155 households → 66,07 GWh/year

These values are introduced into EnergyScope as final thermal energy demands, allowing the model to optimally allocate energy carriers for cooking across different technologies and fuels.

Resources

A crucial component of the model is the definition and allocation of energy resources available to each region. As previously discussed, it is assumed that the modeled regions possess no local availability of fossil energy carriers. In other words, the regional resource potential for natural gas, diesel, or other imported fuels is considered to be zero. Consequently, these fuels must be fully imported to meet the energy needs of the system.

An exception is made for biomass. Based on regional availability, the Lowlands and Valleys are assumed to have sufficient local biomass to cover their respective energy needs related to biomass-based technologies. In contrast, the Highlands are not considered to have significant biomass potential due to limited resource availability in that area. Therefore, no internal biomass resource is modeled for the Highlands region.

In contrast to these fuels, renewable resources such as wind and solar are assumed to be locally available but subject to physical and land-use constraints. Therefore, their use is not unlimited: a maximum installed capacity is defined for each technology in each region to reflect realistic deployment limits.

Wind Resources

Wind energy is considered a local renewable resource, but its potential is not assumed to be unlimited. For this reason, the model imposes an upper bound on the installed wind capacity in each region, based on the availability of land and the spatial distribution of unelectrified areas.

To establish these limits, Bolivia was divided into the three macro-regions defined throughout this study: Highlands, Lowlands, and Valleys. Within each of these zones, only municipalities that are not yet fully electrified were selected for analysis. These municipalities were identified using the spatial electrification dataset introduced previously in Section 2.2.2. They represent the areas where new wind installations are most likely to occur due to the lack of access to centralized electricity infrastructure.

Figure 2.10 shows the geographical distribution of non-electrified municipalities in Bolivia. Each color corresponds to one of the main regions: Highlands (blue), Lowlands (green), and Valleys (orange).

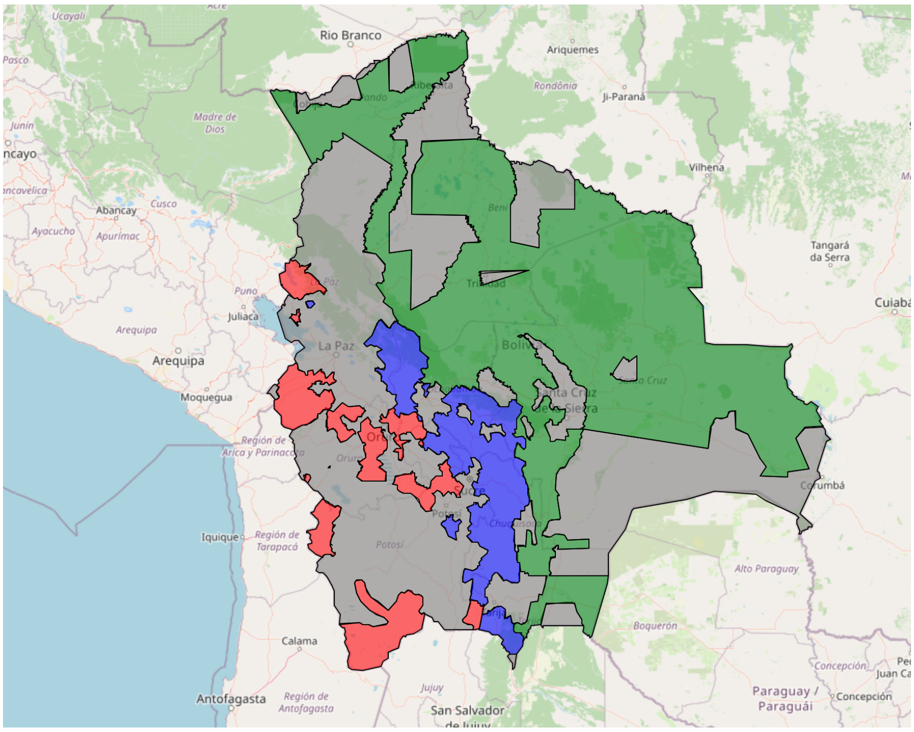

Figure 2.10: Non-electrified municipalities in Bolivia

Based on this regional classification, and with the support of co-supervisor Pablo Jiménez Zabalaga, the necessary input data were generated for integration into EnergyScope. These include both the hourly capacity factor time series and the maximum wind generation potential for each region. The data were produced using a high-resolution geospatial simulation tool currently under development, which will be presented in the upcoming work titled *Multi-Scale Wind-Solar Energy Assessment with Infrastructure Cost Integration: A Case Study of Bolivia* [25]. This study extends the capabilities of the *atlite* framework [26], leading to a Bolivian-specific version known as atlite-BO.

For each municipality, the technical wind potential was estimated and then aggregated according to its corresponding region. This process yielded the following maximum wind capacity values used in the model:

- **Highlands**: 40.184,56 MW
- **Lowlands**: 78.208,55 MW
- **Valleys**: 17.155,56 MW

PV Resources

As with wind energy, photovoltaic (PV) deployment is also subject to regional capacity limits. These constraints reflect realistic land-use, technical, and spatial considerations. The same methodology described in the previous subsection was used to estimate the maximum installable PV capacity in each region.

Based on high-resolution geospatial simulations developed in the context of the atlite-BO framework [25,26], and considering only municipalities that are not fully electrified, as Figure 2.10, the maximum PV capacity for each macro-region was calculated as follows:

- **Highlands**: 1.273,53 MW
- **Lowlands**: 1.065,21 MW
- **Valleys**: 11.158,01 MW

These limits are implemented in the model to ensure that solar deployment remains consistent with the physical availability of suitable land and solar irradiation potential in each region.

Technologies

This section describes the technologies considered for electricity generation in the newly defined regions. Most of the technologies were already available and pre-modelled in the original EnergyScope framework [16]. Only two additional technologies have been introduced specifically for this study, and these are discussed in detail in the following subsections.

Diesel Generators

Diesel-based electricity generation has been included in the model due to its common use in remote and unelectrified areas. Diesel is considered the most accessible and practical fossil fuel for electricity generation in isolated contexts, primarily because it can be transported and stored without requiring extensive infrastructure.

For this reason, natural gas has been excluded from the modelling of the new regions. Its distribution and storage demands make it considerably more complex to implement in remote regions compared to diesel.

Diesel Gensets: This category represents stationary diesel generation systems, typically deployed in microgrids to supply electricity to small communities or clusters of consumers. These systems are already included in the standard EnergyScope configuration, and their techno-economic parameters have been retained without modification.

Diesel Home Systems: In addition to microgrid-scale gensets, small and generally portable diesel generators are also considered to supply isolated households. These systems reflect real-world practices in remote areas, where diesel offers a simple and reliable energy solution. While their operational characteristics are similar to those of stationary gensets, their investment and operating costs have been adapted to reflect household-scale deployment, with all other technical parameters remaining consistent with the original diesel genset implementation.

Wind Energy

Wind energy has also been included in the model, as it is one of the most widely deployed renewable electricity sources worldwide. Its mature technological development, scalability, and competitive costs make it a relevant option for expanding access to electricity in Bolivia's unelectrified regions.

As described before, the potential for wind deployment has been evaluated regionally, and a maximum installed capacity has been defined for each zone based on spatial and technical constraints.

Photovoltaic (PV) Technologies

Regarding solar energy, the EnergyScope Bolivia framework already includes two distinct photovoltaic (PV) technologies for electricity generation. For this study, a third variant has been added to better represent off-grid electrification needs. These three PV technologies are described below.

Utility-Scale PV: The first option corresponds to utility-scale solar installations, which involve large surface areas and high installed capacities. This configuration is typically used to achieve economies of scale and reduce the cost per unit of electricity generated. It is more suitable for centralized deployment where land availability and grid connection are feasible.

Rooftop PV: The second technology models rooftop solar systems, which are better suited to smaller-scale applications and decentralized areas. Rooftop PV typically entails lower investment and maintenance costs per household, and it does not require dedicated land. This makes it particularly relevant for dispersed communities or peri-urban zones with some degree of infrastructure.

Solar Home Systems (SHS): To complement these technologies, a third option has been introduced: Solar Home Systems (SHS). These systems are designed to serve a single household independently and are especially useful in remote areas where grid extension or inter-household connectivity is not viable. SHS include a photovoltaic panel and a dedicated battery system to ensure energy availability across the day.

The modeling of SHS assumes similar operational behavior to that of rooftop PV systems. Therefore, the same set of equations from the original EnergyScope implementation has been reused for consistency. Similarly, battery storage associated with SHS is modeled using the same lithium-ion technology as already implemented in previous versions of the model, ensuring alignment with established storage assumptions.

Lithium-Ion Batteries

In addition to generation technologies, the model also includes energy storage systems, specifically lithium-ion batteries. These batteries allow for temporal balancing between electricity supply and demand, especially in systems with high shares of variable renewable generation.

All information related to lithium-ion battery modeling has been inherited directly from the existing EnergyScope Bolivia framework. This includes performance parameters, cost assumptions, and operational constraints, ensuring consistency with previous studies conducted using the model.

Solar Thermal

Solar thermal technology is also considered in this work. This technology does not generate electricity but provides a source for water heating, thereby reducing electricity consumption. It thus contributes both to saving electricity and to meeting energy demand. This technology was already included in the version of EnergyScope used in this study, and therefore all its existing equations and data are taken into account.

Time Series

For a correct simulation of this scenario, it is essential to provide hourly time series over a full year for key energy demands. Three demand categories are considered in the EnergyScope model: electricity, heating, and space cooling. Each demand profile is differentiated across the three defined regions: Highlands, Lowlands, and Valleys.

The original demand data was obtained from RAMP, which provides high-resolution demand profiles at one-minute intervals. These were aggregated to hourly values to match the input requirements of EnergyScope. For instance, in the case of electricity, the sum of all electricity-related end uses was computed and aggregated by hour, resulting in a complete annual time series for each region. This allows the model to capture seasonal and diurnal variations in electricity consumption patterns.

A similar procedure was followed for heating and space cooling demands. Each category was processed independently to ensure that the final time series accurately reflected regional climatic differences and typical usage profiles.

In addition to demand profiles, it is also necessary to include hourly capacity factor time series for both wind and solar technologies. These time series define the proportion of installed renewable capacity that is available at each hour of the year and are critical to model the variability of renewable energy production. The generation of these profiles is based on the methodology described in the wind resources section, taking into account the Atlite-BO model [26].

Costs

All technology costs used in this study are based on the values provided in the article *Towards a Sustainable Bolivian Energy System in 2050* [15]. This reference includes both investment and operational costs for a wide range of technologies, and it also provides cost projections for future years, specifically 2035 and 2050, which are directly incorporated into this work.

For existing technologies already included in EnergyScope BO, these costs are adopted without modification. However, several new technologies have been introduced in this study, such as Solar Home Systems (SHS), Diesel Isolated Systems, and their associated battery storage. These were not covered in the original article, and therefore required an independent estimation of their 2024 costs.

To ensure consistency, the cost projections for these new technologies in 2035 and 2050 were derived based on the cost evolution of similar technologies already present in the model. For instance:

- SHS follow the same cost reduction trend as rooftop PV systems.
- Diesel Isolated Systems are scaled in line with conventional diesel genset costs.
- Battery storage costs evolve similarly to lithium-ion batteries already implemented in EnergyScope.

The following subsections describe in detail how the base-year (2024) costs for the newly introduced technologies were obtained. These values serve as the starting point for future projections and are critical for the accurate modeling of decentralized electrification pathways.

Solar Home Systems Costs: To estimate the cost of Solar Home Systems (SHS), this study relies on the analysis presented in [27], which evaluates the economic feasibility of off-grid photovoltaic systems in remote communities in Raqaypampa, Bolivia. The context and scale of this study closely match the assumptions in this thesis, making it a highly suitable and reliable source for cost estimation.

Among the different system configurations evaluated in the original work, Scenario 3 is the one that best represents the conditions of this thesis. That configuration corresponds to a household with three or more inhabitants, comparable to the average of 3,14 persons per household observed in this study and includes 160 Wp solar panels and 921,6 Wh battery capacity. These system sizes are considered reasonable for isolated households operating under energy sufficiency assumptions.

The purpose of this reference system is not to model exact component sizes but to derive unit costs per installed power or storage capacity. These unit costs are then scaled appropriately in the simulation, depending on the capacity that EnergyScope determines optimal to install.

PV subsystem:

- Polycrystalline solar panel (160 Wp): 120,9 €
- Inverter (1200 W): 576 €
- Cabling, protection, and mounting structure: 43,2 €
- **Resulting investment cost:** 4746,75 M€/GW
- **Operation and maintenance cost:** 8,6 €/kW/year [28]

Battery subsystem:

- Battery (921,6 Wh): 474,8 €
- Charge controller (50 A): 74,44 €
- Cabling, protection, and mounting structure: 43,2 €
- **Resulting investment cost:** 658,82 M€/GWh
- **Operation and maintenance cost:** 8,6 €/kW/year [28]

These values represent the reference 2024 costs for Solar Home Systems, and will serve as the baseline for future projections in the years 2035 and 2050, following the methodology described previously.

Diesel Isolated Systems: Diesel generators are also considered as a decentralized solution for electrifying isolated households. In this case, unit costs are based on data for small-scale diesel systems, relevant to rural Bolivian contexts.

According to the study presented in [29], which analyzes electrification options for remote communities in Bolivia, the investment cost of such systems is estimated at $1480 per kW. This corresponds to approximately 1302,41 M€/GW when converted to EnergyScope's required format. Additionally, operation and maintenance costs are set at 4,5 €/kW/year, based on values from [30].

All other technical characteristics of this technology are assumed to be the same as the existing Genset-Diesel technology in EnergyScope. Only the cost parameters have been adjusted to reflect the specific context of isolated, standalone diesel generation.

This allows the model to distinguish between centralized and isolated diesel generation in both investment cost and deployment strategy, while reusing consistent operational modeling.

2.4.5 Future Simulations

Estimating Future Demand for 2035 and 2050

To simulate energy scenarios for future years, it is necessary to estimate the expected energy demand for 2035 and 2050 in the regions considered in this study. Under the assumption of energy sufficiency, it is expected that the energy consumption per capita remains constant over time. Therefore, future energy demand is assumed to evolve proportionally to the projected population of each region.

Since demographic projections are only available for a limited number of years, an exponential growth model was used to interpolate and extrapolate population data. Specifically, the growth rate is calculated from the population figures between 2012 and 2024 using the following expression:

$$r = \frac{\ln\left(\frac{P_{2024}}{P_{2012}}\right)}{2024 - 2012} \tag{2.7}$$

Here, P_{2024} and P_{2012} are the known population values for the years 2024 and 2012, respectively, obtained from INE [7], and r is the exponential annual growth rate. This rate is then used to estimate the projected populations for 2035 and 2050 by applying the following formulas:

$$P_{2035} = P_{2012} \cdot e^{r\cdot(2035-2012)} \tag{2.8}$$

$$P_{2050} = P_{2012} \cdot e^{r\cdot(2050-2012)} \tag{2.9}$$

This approach provides a consistent basis for scaling future energy demands across all sectors and end-uses. The resulting projected demands for each region are then used as inputs to the EnergyScope Multicell model for 2035 and 2050 simulation scenarios.

Using these formulas, population growth was calculated at the municipal level and aggregated for each of the three macro-regions. The projected population values for the years 2012, 2024, 2035, and 2050 are presented in Table 2.6, along with the corresponding population growth factors. It should be noted that these figures represent the total population of the aggregated municipalities, and not only the unelectrified population within these regions, since it is assumed that population growth applies equally to both the total and the unelectrified population.

Table 2.6: Population projections and growth factors by region

Region	**Population 2012**	**2024**	**2035**	**2050**
Valleys (0)	2.643.839	2.882.974	3.228.599	4.005.217
Highlands (1)	3.665.828	3.970.214	4.562.185	6.397.549
Lowlands (2)	3.750.189	4.258.672	4.952.422	6.518.043

Region	**Growth 2024–2035**	**Growth 2024–2050**	**Growth 2035–2050**
Valleys (0)	1,1199	1,3893	1,2405
Highlands (1)	1,1491	1,6114	1,4023
Lowlands (2)	1,1629	1,5305	1,3161

Once population projections have been obtained, they are used to scale the energy demand for the future scenarios. Since the baseline demand in 2024 is modeled based on the number of unelectrified households, it is assumed that in future years, these households have been electrified according to the simulation results discussed later in this thesis.

However, the demand from these communities is expected to grow proportionally to the population. Under the sufficiency-based assumption, each person consumes the same amount of energy regardless of the year, implying that demand increases linearly with population growth. Therefore, future demands are calculated by multiplying the 2024 demand by the corresponding population growth factor for each region and target year.

The population growth factors used for this scaling are summarized below:

Table 2.7: Demand scaling factors by region

Region	Factor 2024–2035	Factor 2024–2050
Valleys (0)	1,1199	1,3893
Highlands (1)	1,1491	1,6114
Lowlands (2)	1,1629	1,5305

These factors are applied to all time series demand inputs for each region, including electricity, heating, and space cooling. This approach ensures a coherent demand evolution for the future simulations in 2035 and 2050, while maintaining consistency with the assumptions of sufficiency and constant per-capita consumption.

Changes in Future Simulations

In order to reflect expected technological advancements and improvements in living standards, future simulations for the years 2035 and 2050 incorporate additional cooking technologies beyond traditional biomass use. In the 2024 baseline, cooking is primarily based on rudimentary biomass stoves, which are generally built in an artisanal manner. Such devices are typically inefficient and, in many cases, produce incomplete combustion, leading to higher emissions of pollutants and lower overall performance. These limitations make them unsuitable for long-term sustainable energy planning.

For the future scenarios, it is assumed that access to more modern and efficient cooking solutions becomes feasible across all regions. Therefore, the following technologies are included in the model for all regions in the 2035 and 2050 simulations:

- Liquefied Petroleum Gas (LPG) stoves
- Natural Gas (NG) stoves
- Electric cookers

This change reflects a transition towards cleaner and more efficient energy sources for domestic use, in line with national development goals and improved rural electrification strategies. By including these technologies, the model better represents realistic options for the future Bolivian energy mix, particularly in rural and newly electrified areas.

2.5 Integrated Modeling: Embedding Remote Communities into EnergyScope

We extend EnergyScope with off-grid Home System (HS) technologies (e.g., `PV_HS`, `BATT_HS`, `DIESEL_HS`) to supply the newly defined remote cells. This required specific modifications to the model equations so that these technologies are explicitly represented. In addition, new constraints were introduced to ensure their proper operation. The following subsections present these contributions.

2.5.1 HS Battery Charging Constraint

To ensure that Home System (HS) batteries are charged only by local photovoltaic generation, we constrain the hourly charging flow of the HS battery to be no larger than the PV_HS output on the electricity layer. This prevents diesel-based HS generation (or any grid flow) from charging the HS battery, while preserving the standard hourly balance on the ELECTRICITY layer.

$$\mathrm{Sto_{in}}(r, \mathrm{Batt\_HS}, \mathrm{Electricity}, h, td) \ \leq \ f(\mathrm{PV\_HS}, \mathrm{Electricity}) \ F_t(r, \mathrm{PV\_HS}, h, td) \quad (2.10)$$

Here, $\mathrm{Sto_{in}}$ denotes the battery charging flow on the electricity layer, F_t the hourly operation of the PV_HS technology, and $f(\cdot, \mathrm{ELECTRICITY})$ the layer incidence coefficient (positive for electricity outputs). All other symbols follow Section 2.4.1.

2.5.2 Population Density Criterion for Off-Grid Electrification

Due to the technical and economic difficulty of connecting highly dispersed communities to an electricity network, a population density criterion has been adopted to determine which areas must be electrified exclusively through Home System technologies, such as the Solar Home Systems and Diesel Isolated Systems described earlier.

To distinguish between grid-feasible and off-grid households, the population density of each municipality was analyzed. If the density falls below a defined threshold, it is assumed that the households are too sparsely distributed to be connected via grid extension or even a local microgrid. In such cases, electrification must be achieved through individual Home Systems.

The threshold selected is **25 households per km²**, a value established in agreement with the thesis co-supervisor, Claudia Sánchez Solís, an expert in rural electrification with specific experience in the Bolivian context. As a result, all municipalities with a household density below this value are assigned to off-grid electrification using decentralized systems.

Using the geospatial and demographic data compiled earlier, as explained in Section 2.2.2, the number of unelectrified households in low-density municipalities was identified and then aggregated into the region to which each municipality belongs. The results for each region are as follows:

- **Valleys:** 38.018 households
- **Highlands:** 28.446 households
- **Lowlands:** 43.033 households

Based on the total number of unelectrified households per region, the proportion that must be electrified through Home Systems can be calculated. These shares represent the minimum electricity that must be generated using off-grid technologies in each region:

- **Valleys:** 77,34%
- **Highlands:** 100%
- **Lowlands:** 76,23%

These minimum shares are implemented as constraints in the model to ensure that each region meets the required level of off-grid electrification. This modeling decision also reflects the need to electrify not only residential households but also decentralized infrastructures such as schools, health centers, and community buildings.

Implementation in the model: Let $eut \equiv \text{ELECTRICITY}$ and define a regional parameter $\text{share}_{\text{HS}}(r) \in [0, 1]$ with the values reported above (Valleys 0.7734, Highlands 1.0, Lowlands 0.7623). The following constraint enforces that, in every region and at every time slice, the contribution from HS technologies (solar, diesel and associated storage) must be at least equal to the required minimum share of total electricity injections:

$$\sum_{\substack{j \in TECH\_HS \setminus STO \\ f(j,eut)>0}} f(j, eut)\, F_t(r, j, h, td) \;+ \sum_{k \in TECH\_HS \cap STO} \Big(\text{Sto}_{\text{out}}(r, k, eut, h, td) - \text{Sto}_{\text{in}}(r, k, eut, h, td)\Big)$$
$$\geq \; \text{share}_{\text{HS}}(r) \left[\sum_{\substack{j \in TECH \setminus STO \\ f(j,eut)>0}} f(j, eut)\, F_t(r, j, h, td) \;+ \sum_{\substack{i \in RES \\ f(i,eut)>0}} f(i, eut)\, R_{t,\text{imp}}(r, i, h, td) \right] \quad (2.11)$$
$$\forall\, r \in REG,\; h \in H,\; td \in TD.$$

All symbols follow Section 2.4.1: F_t is the hourly technology operation, $f(\cdot, eut)$ the layer incidence coefficient (positive on outputs), $\text{Sto}_{\text{in/out}}$ the storage charging/discharging flows, and $R_{t,\text{imp}}$ interregional imports on the electricity layer.

2.5.3 Electrical Losses

Electrical losses are an important aspect of system modeling, particularly when comparing centralized and decentralized electricity supply options. In the case of Home Systems (HS), including solar home systems, diesel isolated systems, the physical distance between generation and consumption is minimal. As a result, transmission and distribution losses are significantly lower than those in grid-connected systems.

Based on [31], a loss factor of only **2%** is assumed for all Home System technologies. This is considerably lower than the default **16%** loss factor applied to grid-based electricity distribution, as already defined in the standard EnergyScope BO configuration.

To represent this distinction, the original loss accounting (Eq. 1.38 in [23]) is split into two parts: grid-connected technologies (excluding storage and HS) and HS technologies (also excluding storage). Losses are computed as a fixed percentage of the positive injections on the electricity layer ($eut \equiv \text{ELECTRICITY}$ in this case). For grid-connected systems, these injections include both the outputs of technologies on the electricity layer and the net electricity imported from other regions. For HS, by contrast, injections correspond exclusively to the outputs of HS technologies, as by definition they do not rely on interregional imports. The resulting constraints are:

$$\begin{aligned}\mathrm{Net}_{\mathrm{loss}}^{\mathrm{grid}}(r, eut, h, td) = \Bigg(& \sum_{\substack{j \in TECH \setminus (STO \cup TECH\_HS) \\ f(j,eut)>0}} f(j, eut)\, F_t(r, j, h, td) \\ & + \sum_{\substack{i \in RES \\ f(i,eut)>0}} f(i, eut)\, R_{t,\mathrm{imp}}(r, i, h, td) \Bigg) \cdot \%\mathrm{net}_{\mathrm{loss}}(eut)\end{aligned} \tag{2.12}$$

$$\mathrm{Net}_{\mathrm{loss}}^{\mathrm{HS}}(r, eut, h, td) = \Bigg(\sum_{\substack{j \in TECH\_HS \setminus STO \\ f(j,eut)>0}} f(j, eut)\, F_t(r, j, h, td) \Bigg) \cdot \%\mathrm{net}_{\mathrm{loss\ HS}}(eut) \tag{2.13}$$

with $\%\mathrm{net}_{\mathrm{loss}}(eut) = 16\%$ for grid distribution and $\%\mathrm{net}_{\mathrm{loss\ HS}}(eut) = 2\%$ for HS in this work. Total network losses are defined as

$$\mathrm{Net}_{\mathrm{loss}} = \mathrm{Net}_{\mathrm{loss}}^{\mathrm{grid}} + \mathrm{Net}_{\mathrm{loss}}^{\mathrm{HS}}.$$

All symbols follow Section 2.4.1: $f(\cdot, eut)$ are layer incidence coefficients (sign indicates consumption/production on the layer), F_t is the hourly technology operation, and $R_{t,\mathrm{imp}}$ denotes interregional imports on the electricity layer (excluded from the HS case by construction).

This split ensures that electricity generated and consumed locally via Home Systems is not unfairly penalized by grid-scale transmission losses, while maintaining consistency with centralized system modeling.

3. Results

3.1 RAMP Simulation

After defining the required inputs and configurations in RAMP, this section reports the simulated demand used in the subsequent EnergyScope optimization.

3.1.1 Demand Analysis

We generated a standard set of plots to characterise the simulated demand. To keep the main text concise, we discuss in detail the three views only for Households, for Community Services and IGAs we show only the full-year profile. The complete collection for all regions and sectors is provided in Appendix A. Note that these plots are illustrative; the quantity actually passed to EnergyScope is presented later.

Annual demand profile: Hourly electricity demand over a full year, with seasonal divisions marked. The x-axis starts on 21 December (Southern Hemisphere summer) and spans 12 months. This view highlights seasonal effects (e.g., weather-dependent loads) and the overall level and variability of demand.

Average daily profile: Typical diurnal shape obtained by averaging the minute-level series over all days of the year. It reveals the timing and relative magnitude of daily peaks and shoulders across end-uses.

Annual load-duration curve (LDC): Hourly demand values sorted in descending order to assess peakiness and stability. The LDC indicates whether a profile is dominated by short, intense peaks or exhibits a more regular, near-baseload component.

Households

The most significant demand sector analysed is that of households. A selection of representative cases in the different regions is presented to illustrate the key behavioural patterns of household electricity demand across different geographic contexts.

Full-year profile (Highlands): Figure 3.1 shows the annual demand profile for all household-related electricity uses in the Highlands region. The most dominant and energy-intensive input is water heating, shown in purple. This is due to the high amount of energy required to heat water, especially in colder months. The seasonal evolution of this demand follows an expected pattern, increasing during winter and decreasing as ambient

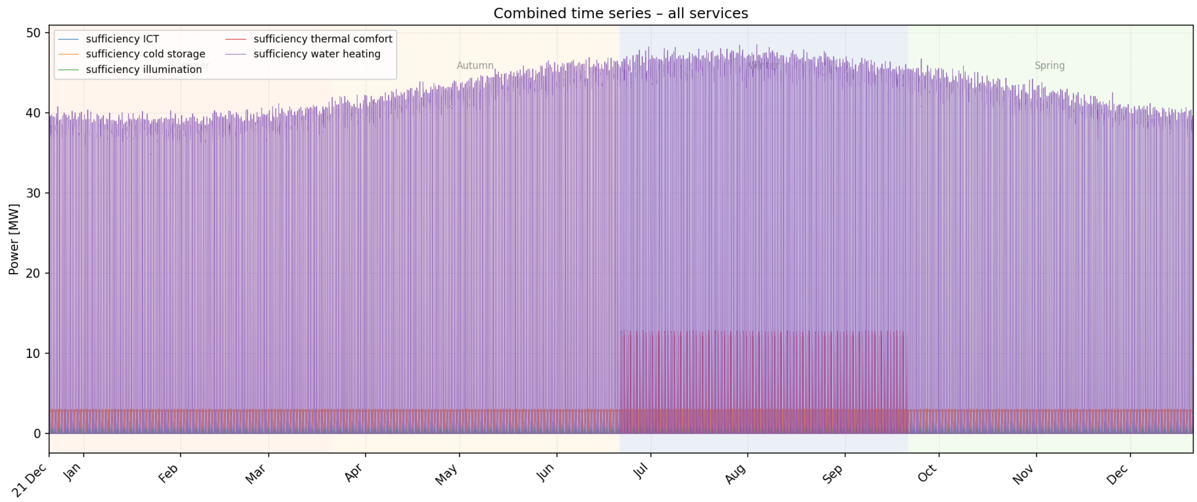

Figure 3.1: Annual demand profile for households in the Highlands

temperatures rise in the summer months of the southern hemisphere. The peak demand for this input occurs in August, reaching approximately 45 MW.

Another relevant behaviour is observed in the thermal comfort demand, represented in red. As discussed in Section 2.3.3, this input corresponds to heating and is only considered active during winter months in the Highlands. This modelling assumption results in a sharp change in demand during winter, producing a step-like profile that may appear abrupt or unrealistic. A possible improvement would be to implement a more gradual seasonal transition to better reflect real-world heating needs.

Although it may appear red, the orange area in the figure corresponds to cold storage, which was modelled as a constant demand throughout the year. Finally, ICT and lighting, depicted in lighter colour, contribute relatively little to the total demand and remain stable over the seasons.

Average daily profile (Lowlands): Figure 3.2 presents the average daily electricity demand profile for household uses in the Lowlands region. This type of plot highlights how demand patterns align with typical human behaviour throughout the day.

Among the most prominent inputs is water heating (shown in purple), which exhibits two distinct peaks, one in the morning and another in the evening, corresponding to the expected times of hot water use for showering. Another interesting behaviour is observed in the ICT input (in blue), which was modelled to concentrate most of its usage in the afternoon hours. Lighting (in green) also follows a logical pattern, with demand increasing during periods of low natural light, such as early morning and late evening.

Load-duration curves (Valleys): To conclude the household demand analysis, Figure 3.3 displays the load-duration curves for each household input in the Valleys region. These curves allow for an assessment of the consistency and intensity of electricity use over the course of the year.

Water heating and heating exhibit relatively high peak demands but low overall regularity. This is expected, as water heating occurs at specific moments of the day, while heating is only active during colder months. In contrast, cold storage shows a nearly constant demand profile, reflecting the modelling assumption that refrigeration systems

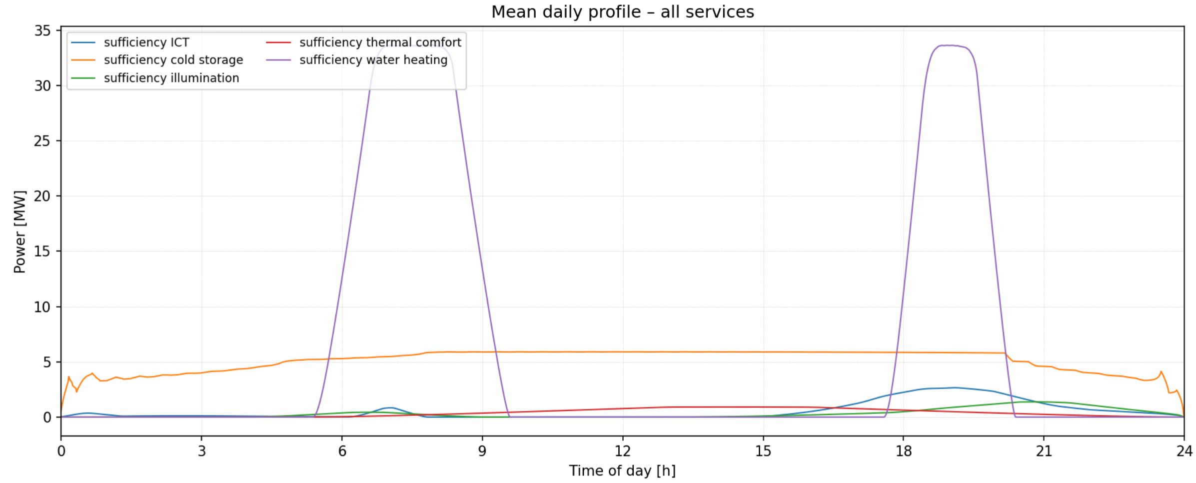

Figure 3.2: Average daily pattern for Households in the Lowlands

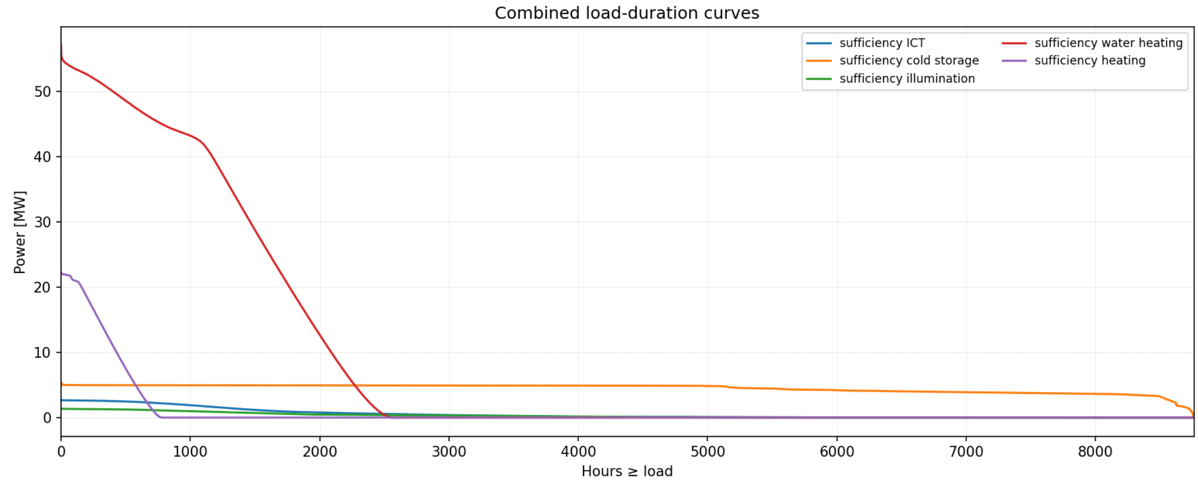

Figure 3.3: Annual Load-Duration Curves for Households in the Valleys

must remain active year-round to preserve food.

ICT and lighting present lower peak values compared to other inputs, but their curves indicate a less stable usage pattern. This is due to their concentration in particular time windows each day, rather than continuous operation.

Community Services

This subsection presents the results for the Community Services demand category. Here, only the Highlands region is analysed with the full-year profile, as it provides a clear and representative visual interpretation of the simulated demand patterns.

Full-year profile (Highlands): Figure 3.4 shows the annual demand profile for all community service infrastructures considered in the model. Among these, public lighting is by far the most significant contributor to electricity demand. This is primarily due to the high number of lighting poles assumed per settlement, in contrast to the smaller number of schools or health centers included. As a result, the demand from other community service infrastructures appears relatively small in comparison.

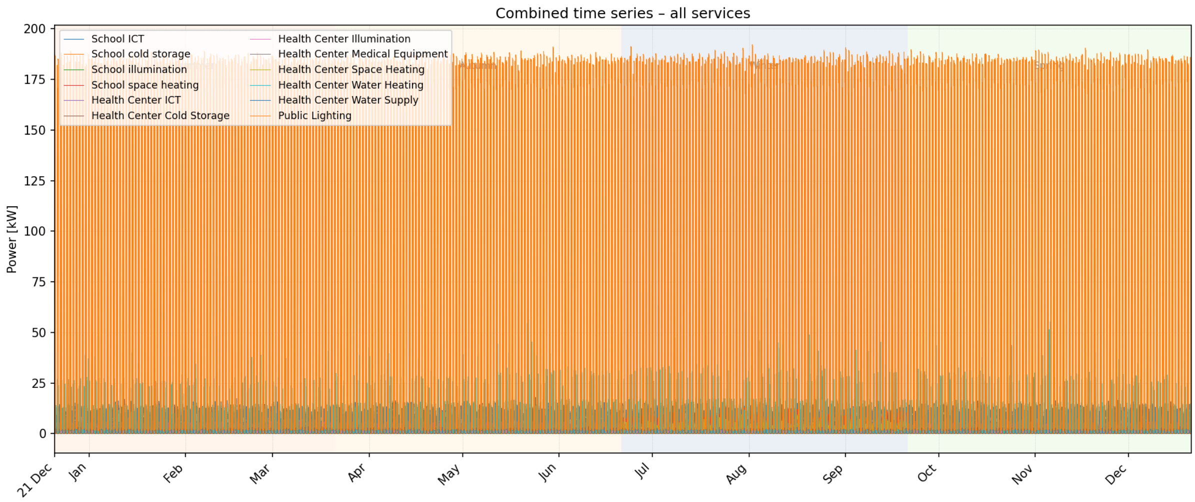

Figure 3.4: Annual demand profile for community services in the highlands

IGAs

Finally, we present the simulation results for the Income-Generating Activities (IGAs) category.

Full-year profile (Lowlands): Figure 3.5 shows the annual demand profile for the Lowlands region. A notable feature in this figure is the presence of periodic drops in demand, which are due to the assumption that some IGAs do not operate during weekends, under the rationale that many rural economic activities pause on non-working days. This pattern is especially visible in the two main contributors to demand: flour processing (in red) and entertainment business illumination (in green).

Figure 3.5: Annual demand profile for IGAs in the Lowlands

3.1.2 Cross-regional Comparison

The first comparison focuses on the magnitude of electricity demand by input type, disaggregated by region. Figure 3.6 shows that the two most significant inputs are water heating and cold storage.

In the case of water heating, the demand is strongly influenced by the ambient temperature of each region, as the input was modelled to depend directly on local groundwater temperature. As a result, water heating demand is more prominent in the Highlands and Valleys, where colder conditions increase the energy required.

As shown for cold storage, the region with the highest demand is the Lowlands, since it is the hottest area and the only one modelled with a higher power requirement compared to the other regions.

To provide an alternative representation, Figure 3.7 displays a heatmap showing the relative importance and magnitude of each input type across the three regions. This visualisation helps identify which demands are dominant in each region and highlights the differences in electricity needs between them. It also reports the demand level of each input by region, thus providing an indication of their magnitude.

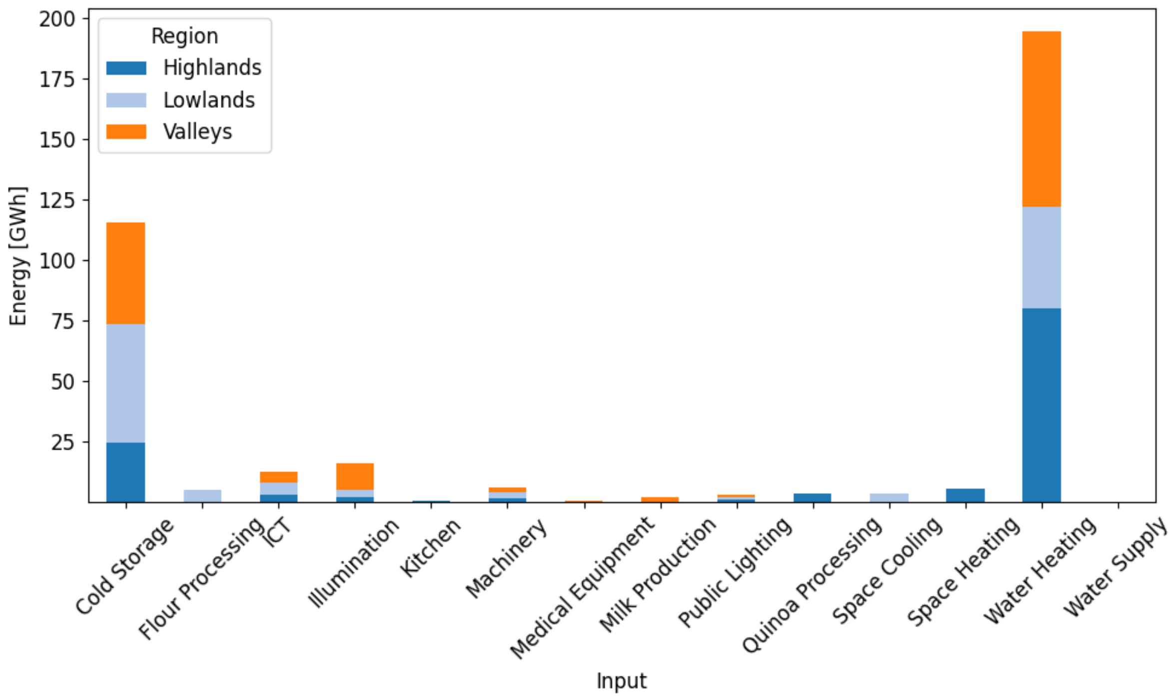

Figure 3.6: Annual electricity demand by input type across Bolivian regions.

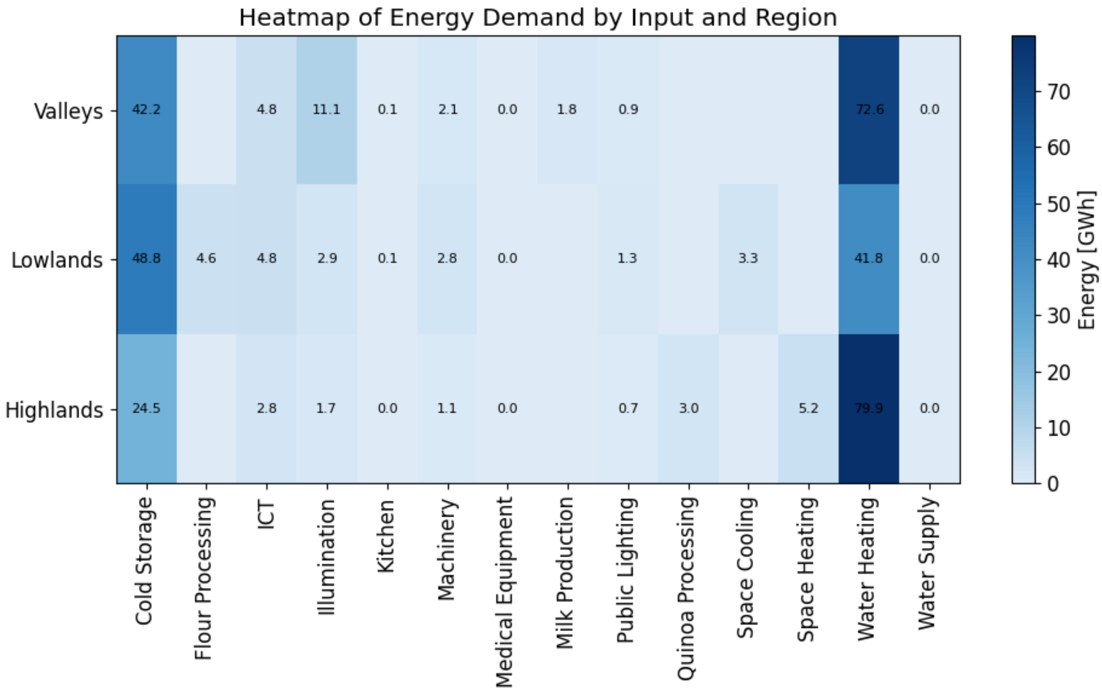

Figure 3.7: Heatmap of electricity demand by input and region

Additional figures providing a sectoral and input-wise breakdown of annual electricity demand for each region are compiled in Appendix A. A comprehensive table summarising the annual demand by input and region is also provided (Table A.1), which complements the graphical analysis.

As a summary, the total electricity demand estimated with RAMP amounts to **365 GWh/year**. This value corresponds to the electricity needs of the 123.077 households considered in the model. Assuming an average household size of 3,14 inhabitants, as justified in Section 2.3.4, the simulated demand represents the requirements of approximately 421.000 inhabitants.

This leads to an average annual electricity consumption of about **866 kWh per inhabitant**, which provides a meaningful reference for assessing the sufficiency of electricity supply in rural Bolivian contexts. According to World Bank data, the electricity consumption per capita in Bolivia was 859,3 kWh in 2022, and by extrapolating the trend from 2016 to 2022, the estimated value for 2024 would be 948,9 kWh per capita [32]. Therefore, it is reasonable that our estimate is slightly lower, given that it focuses on rural areas only.

Moreover, other studies suggest that a minimum of 1.000 kWh per person per year is required to meet modern energy service standards, inclusive of both household and non-household consumption [33]. In this sense, our figure lies close to this threshold, supporting the plausibility and adequacy of the demand quantification performed with RAMP.

3.2 EnergyScope Simulation

This section presents the optimization results obtained with EnergyScope. We first show the results for the newly added remote communities in isolation, in order to understand the technology choices that emerge under the off-grid constraints. We then aggregate across remote regions to assess their total contribution.

The results are structured into three main categories:

1. **Energy representation** – The analysis includes the installed capacity of each technology and the resulting electricity generation mix. These figures provide insight into the technological composition required to meet the electricity demand.

2. **Costs** – Reported costs are annualized values. EnergyScope converts all investment costs, including those related to construction, into annual equivalents by accounting for each technology's lifetime. In this way, both operational and investment-related expenditures are consistently represented on an annual basis.

3. **Emissions** – In this work, the reported emissions correspond exclusively to operational emissions from fossil fuel combustion. Construction-related emissions, such as those associated with manufacturing, transport, and installation, are not included. This approach follows international reporting standards (e.g., IRENA, IEA), which only account for direct operational emissions in national energy balances. Including construction-related emissions would result in double counting, as they are already integrated into national statistics under freight transport and industrial processes.

3.2.1 Remote Communities

Results are organized by target year (2024, 2035, 2050). For each year and region (Highlands, Lowlands, Valleys), we report the electricity generation mix and we discuss how the imposed off-grid share drives technology selection.

2024 Results

Highlands (2024): Figure 3.8 shows the 2024 generation mix for the Highlands. By construction, remote communities in this region are fully supplied by isolated Home Systems, as showed in Section 2.5.2. The model selects a combination dominated by Diesel Home Systems (about 65% of annual electricity), with the remainder covered by Solar Home Systems. This outcome is consistent with the off-grid constraint and with the relative economics and availability of the two options in a baseline year: diesel provides firm energy without storage, while PV-based systems are limited by resource variability and storage requirements.

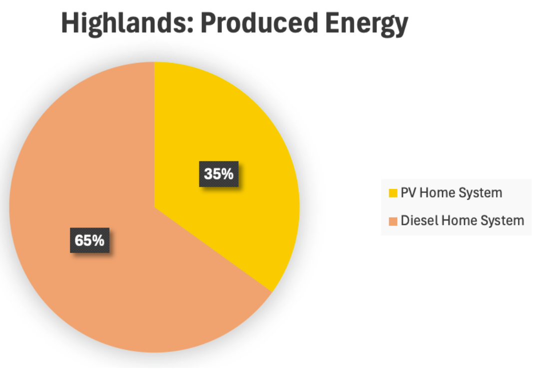

Figure 3.8: Highlands 2024 Energy Mix

Lowlands (2024): In the Lowlands (Figure 3.9), the minimum share of isolated supply is enforced but not at 100%. Consequently, additional technologies appear alongside Home Systems: rooftop PV, wind and biomass contribute a non-negligible part of generation. Even so, isolated Home Systems still account for the majority (77%), satisfying the minimum-share constraint defined in Section 2.5.2.

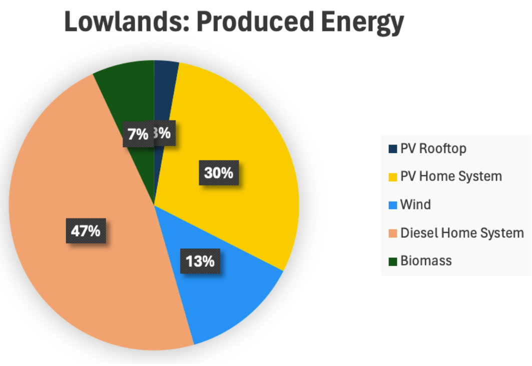

Figure 3.9: Lowlands 2024 Energy mix

Valleys (2024): The Valleys (Figure 3.10) display a composition similar to the Lowlands: isolated Home Systems remain the core supply due to the minimum-share requirement, while rooftop PV, wind and biomass provide complementary contributions where feasible. Differences with the Lowlands are explained by local resource and demand characteristics, but the qualitative picture remains consistent.

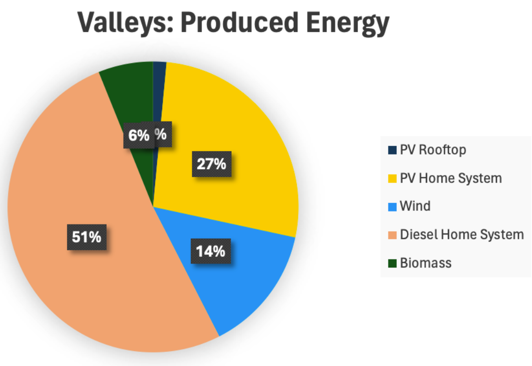

Figure 3.10: Valleys 2024 Energy Mix

Aggregate view (2024): Analysing regions separately is informative, but percentage shares hide the relative weight of each region. We therefore report the *installed capacity mix* (Figure 3.11) and the *generation mix* (Figure 3.12) aggregated over all remote regions.

On the capacity side, most of the installed power belongs to Home Systems, as expected from the regional results. Renewable technologies (PV and wind) exhibit higher installed capacity shares than their generation shares, which is consistent with their lower capacity factors and resource variability. This gap is visible when comparing Figure 3.11 to Figure 3.12: renewables contribute less to annual MWh than to MW, while Diesel Home Systems deliver a larger fraction of energy relative to their installed capacity due to their dispatchability.

Overall, in 2024 the bulk of electricity for remote communities is supplied by Diesel Home Systems, followed by Solar Home Systems, with wind, rooftop PV and biomass

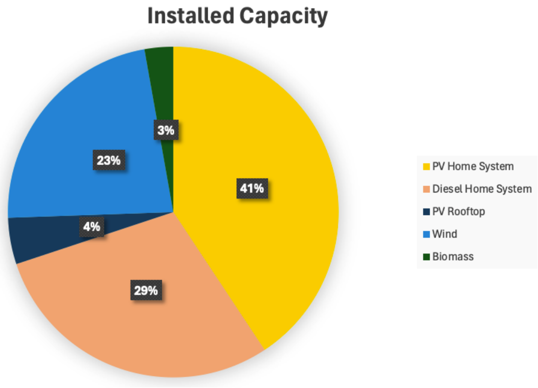

Figure 3.11: 2024 Total Capacity mix

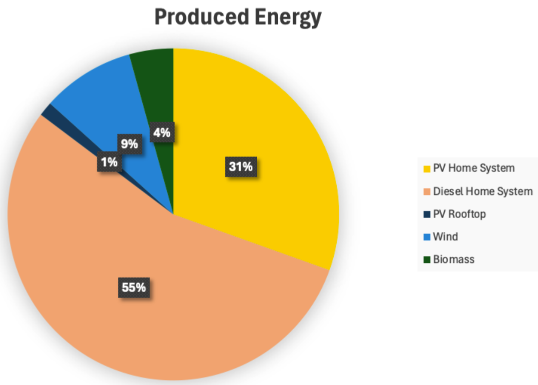

Figure 3.12: 2024 Total Energy Mix

playing secondary roles. This underscores the role of isolated supply in rural contexts under current techno-economic assumptions and imposed service constraints.

Sankey diagram analysis: Figure 3.13 presents a Sankey diagram of the Lowlands energy flows in 2024, showing the pathways from primary energy sources to final uses. The diagram clearly illustrates how electricity is generated and allocated to meet the sectoral demands defined in the RAMP model, with values consistent with the simulated load profiles, seen in A.1. It is also noteworthy that a portion of the heating demand, specifically for hot water, is met by solar thermal systems. In addition, the diagram highlights the cooking demand, which remains substantial and is supplied exclusively by biomass. As discussed earlier, in the 2024 baseline scenario cooking is entirely met through biomass, reflecting the absence of alternative cooking technologies in this time frame.

System costs, storage and emissions (2024, remote regions)

Table 3.1 summarizes the system costs by remote region in 2024. Lowlands and Valleys account for roughly three quarters of the total, with Highlands representing the remaining quarter.

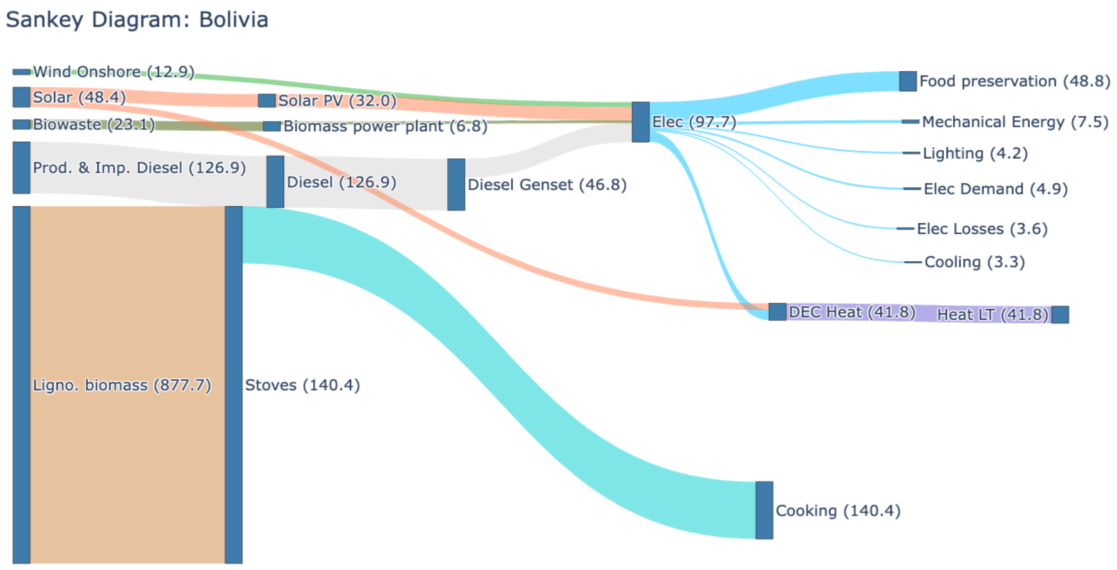

Figure 3.13: LL 2024 Sankey Diagram

Table 3.1: System costs by remote region (2024)

Region	Cost [M€]	Share of total [%]
Highlands	8,38	26,8
Lowlands	11,69	37,3
Valleys	11,24	35,9
Total	**31,31**	**100**

Table 3.2 reports the aggregated installed capacity by technology across all remote regions. Home Systems (PV and Diesel) represent about 70% of total installed power, with wind contributing ∼23%.

Table 3.2: Installed generation capacity by technology (2024, remote regions)

Technology	Capacity [MW]	Share [%]
PV Home System	55,28	40,69
Diesel Home System	39,70	29,22
PV Rooftop	6,17	4,54
Wind	30,92	22,76
Biomass	3,80	2,80
Total	**135,86**	**100,00**

Battery storage: Table 3.3 shows the distribution of battery energy capacity across centralized systems and those embedded in Home Systems. The total installed storage amounts to 133,16 MWh, which corresponds to roughly 1 hour of equivalent full-power operation given the aggregate installed capacity of 135,86 MW. This indicates that storage is dimensioned primarily to smooth short-term fluctuations and support the integration of variable renewables, rather than to provide multi-hour or multi-day autonomy. Diesel Home Systems remain the main source of firm capacity to ensure continuous supply in the absence of renewable generation.

Table 3.3: Installed battery energy capacity (2024, remote regions)

Storage type	Energy capacity [MWh]	Share [%]
Batteries (centralized)	133,16	29,55
Batteries Home System	317,40	70,45
Total	**450,56**	**100,00**

Emissions (2024): With total annual emissions of 918,6 t CO_2 and an aggregate electricity production of 317,403 GWh in 2024, the resulting emission intensity is approximately 2,89 t CO_2/GWh, equivalent to 2,89 kg CO_2/MWh.

2035 Results

This subsection reports the 2035 outcomes for the newly added remote regions, considered in aggregate. The 2035 run is a snapshot approach where installed capacities in 2035 must be at least those deployed in 2024. As a result, percentage shares change only moderately; additional demand is largely met by expanding PV while the diesel share decreases in relative terms.

Figures 3.14 and 3.15 show, respectively, the installed capacity mix and the electricity generation mix. Compared with 2024, PV increases both in percentage in both graphics, while diesel remains the main provider of firm energy but with a lower percentage share.

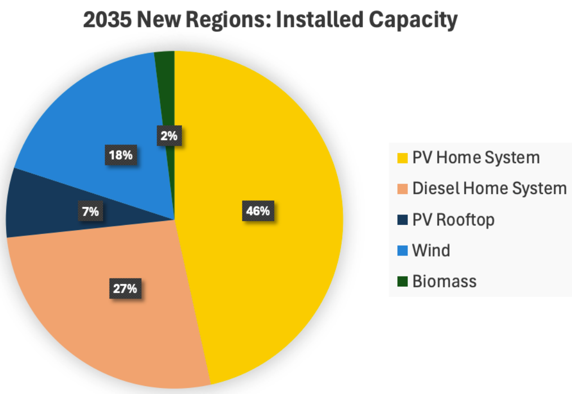

Figure 3.14: 2035 New Regions Capacity Mix

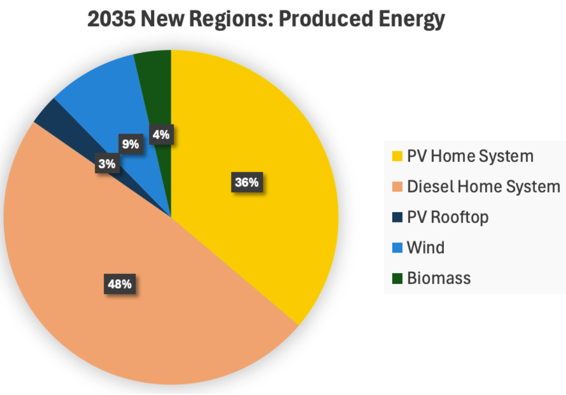

Figure 3.15: 2035 new Regions Energy Mix

Sankey diagram analysis: Figure 3.16 presents the Lowlands energy-flow Sankey for 2035. Electricity flows are allocated consistently with the RAMP-based demands, and a portion of low-temperature heat continues to be supplied by solar thermal. A key change relative to 2024 is observed in cooking: demand remains substantial but is now met predominantly by gas (LPG), as additional cooking technologies become available in the 2035 scenario. The Sankey diagrams of other regions and other years can be found at Appendix B.

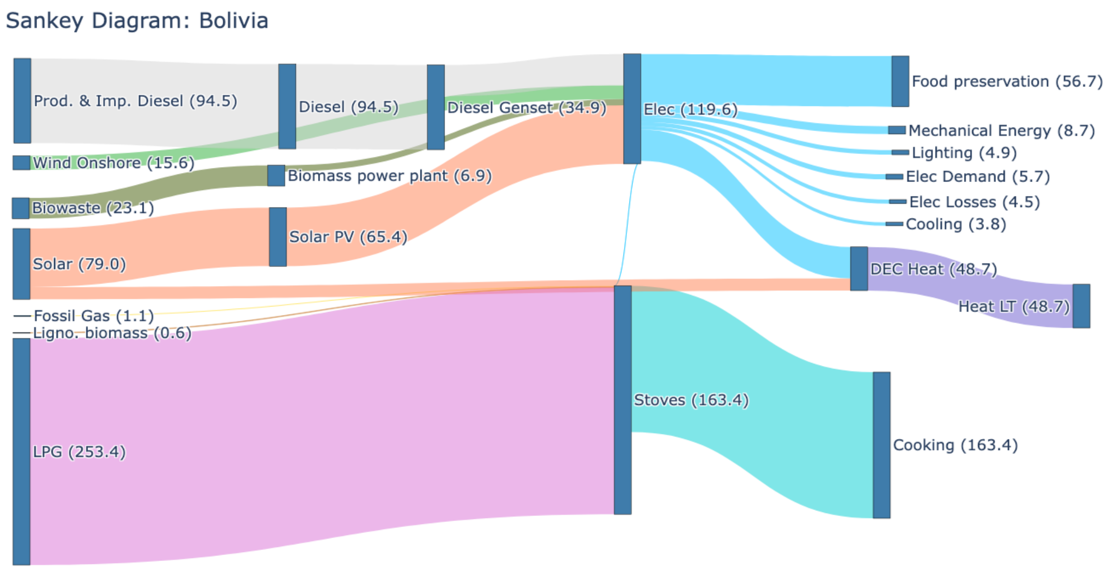

Figure 3.16: Lowlands 2035 Sankey Diagram

Installed capacity and generation. Tables 3.4 and 3.5 report absolute values and shares by technology. Total installed capacity reaches 194,77 MW and total annual generation 377,99 GWh.

Battery storage. Total installed battery energy capacity amounts to 229,30 MWh in 2035. Relative to the aggregate installed power (194,77 MW), this corresponds to about 1,18 hours of equivalent full-power operation. Storage therefore remains sized to smooth

Table 3.4: Installed generation capacity by technology (2035, remote regions)

Technology	Capacity [MW]	Share [%]
PV Home System	90,63	46,53
Diesel Home System	52,16	26,78
PV Rooftop	13,05	6,70
Wind	35,13	18,04
Biomass	3,80	1,95
Total	**194,77**	**100,00**

Table 3.5: Annual electricity generation by technology (2035, remote regions)

Technology	Energy [GWh]	Share [%]
PV Home System	136,76	36,18
Diesel Home System	183,36	48,51
PV Rooftop	11,28	2,99
Wind	32,88	8,70
Biomass	13,72	3,63
Total	**377,99**	**100,00**

short-term fluctuations and support PV integration; firm supply continues to be provided primarily by diesel assets.

Costs and emissions. The total system cost for the remote regions reaches 39,412 M€. Annual emissions amount to 2,23 kt CO_2. This increase versus 2024 reflects both the higher demand and the shift of cooking from traditional biomass to modern fuels (notably LPG).

2050 results

The 2050 run is a snapshot with a roll-forward constraint: installed capacities in 2050 must be at least those deployed in 2035. Higher demand and relaxed constraints within the new regions lead to small entries of additional technologies and a marked shift toward PV-based supply.

Figures 3.17 and 3.18 report, respectively, the installed capacity mix and the electricity generation mix for the aggregated remote regions. New minor contributions (*PV Utility*, *Diesel GENSET*) appear, while *PV Home Systems* become the dominant option in both MW and MWh. *Diesel Home Systems* recede in installed capacity but remain relevant in generation (around 30%). *PV Rooftop* gains weight; *wind* and *biomass* lose relative importance.

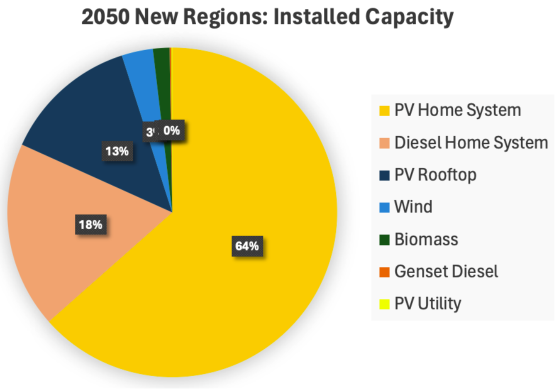

Figure 3.17: 2050 New Regions Capacity Mix

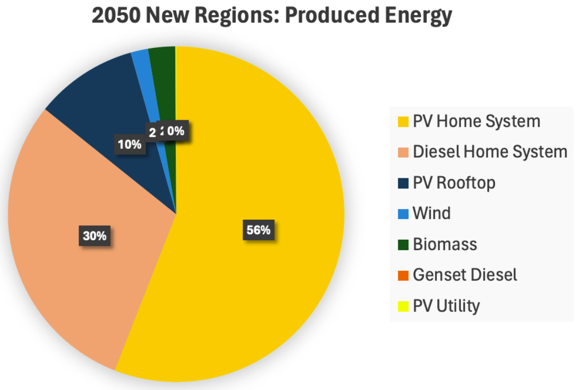

Figure 3.18: 2050 New Regions Energy Mix

Installed capacity and generation: Tables 3.6 and 3.7 report absolute values and shares by technology. Total installed capacity reaches **314,6 MW** and total annual generation **538,6 GWh**.

Table 3.6: Installed generation capacity by technology (2050, remote regions)

Technology	Capacity [MW]	Share [%]
PV Home System	199,65	63,46
Diesel Home System	57,55	18,29
PV Rooftop	41,86	13,30
Wind	9,64	3,06
Biomass	5,13	1,63
Diesel GENSET	0,51	0,16
PV Utility	0,27	0,09
Total	**314,61**	**100,00**

Table 3.7: Annual electricity generation by technology (2050, remote regions)

Technology	Energy [GWh]	Share [%]
PV Home System	301,34	55,95
Diesel Home System	160,61	29,82
PV Rooftop	53,15	9,87
Wind	9,02	1,68
Biomass	13,95	2,59
Diesel GENSET	0,22	0,04
PV Utility	0,30	0,06
Total	**538,59**	**100,00**

Battery storage: Table 3.8 shows the installed battery energy capacity. The total amounts to **656,37 MWh**, equivalent to **2,09 hours** of full-power operation given the aggregate installed power (314,61 MW). Storage remains sized for short-term balancing and PV integration; firm supply is provided primarily by diesel assets.

Table 3.8: Installed battery energy capacity (2050, remote regions)

Storage type	Energy capacity [MWh]	Share [%]
Batteries (centralized)	504,49	76,86
Batteries Home System	151,88	23,14
Total	**656,37**	**100,00**

Costs and emissions: The total system cost for the remote regions reaches **59,28 M€**. Annual emissions are **2,23 kt CO_2**. Absolute emissions remain modest given the limited diesel generation.

3.2.2 Integrating Remote Communities to the National Energy Planning

We now integrate the newly defined remote regions into Bolivia's national energy planning and quantify their system-wide impact. As before, we present results year by year, this subsection focuses on the 2024 baseline.

Comparison with the Current Bolivian System (2024)

Figure 3.19 (installed capacity) and Figure 3.20 (annual generation) report the national mixes after adding remote communities to the Bolivian system (both SIN and existing SAs). The national picture remains broadly consistent with the baseline without remote regions (as shown in Figures 2.8 and 2.9), with a visible but modest contribution from Home Systems driven by the minimum isolated-supply shares imposed for remote areas (see Section 2.5.2).

On the generation side, non-renewable technologies account for slightly above 60% of national electricity in 2024, higher than the share observed in the remote-only case (as seen in Figure 3.12).

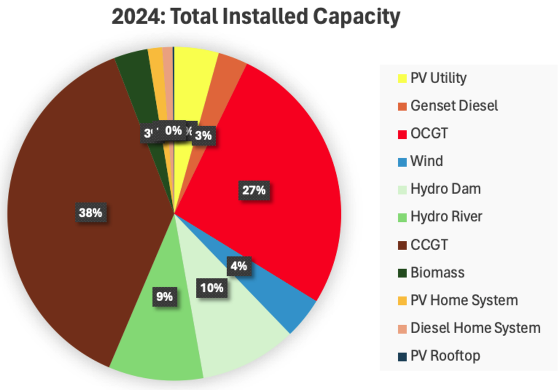

Figure 3.19: Installed capacity mix in 2024 after integrating remote regions into the national system

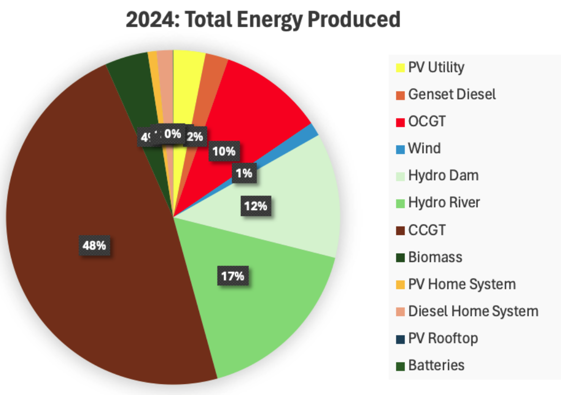

Figure 3.20: Electricity generation mix in 2024 after integrating remote regions into the national system.

System-level impacts (costs, energy, emissions): Table 3.9 summarizes the aggregate impacts of integrating remote regions in 2024. Remote communities represent 2,83% of national electricity (317,40 GWh out of 11198,95 GWh) but 3,89% of total system cost (31,31 M€ out of 805,59 M€). Their share of total emissions is negligible at 0,011% ($ktCO_2$ 0,919 out of $ktCO_2$ 8239,59).

Table 3.9: Integration of remote regions into the national system (2024): system-level metrics.

	National total	Remote regions	Share [%]
System cost [M€]	805,59	31,31	3,89
Electricity [GWh]	11.198,95	317,40	2,83
Emissions [kt CO_2]	8239,59	0,919	0,011

Emissions: The much lower emissions in remote regions are explained mainly by two factors. First, all cooking demand is met with biomass, which is treated as carbon-neutral in this accounting. Second, remote communities show a higher share of renewable electricity (PV and wind) compared to the current Bolivian system, which remains largely based on thermal generation.

Takeaways for 2024: Integrating remote regions barely alters the national generation and capacity mixes, though it introduces a visible Home System footprint in installed power. The cost share of remote areas exceeds their energy share, reflecting dispersed demand and local adequacy requirements. At the national level, the increase in emissions is marginal, consistent with the low-emission technology choices selected for remote communities in the baseline year.

2035 Results

Figures 3.21 and 3.22 show the installed capacity mix and the electricity generation mix for 2035 after integrating all regions. Compared with 2024, we observe a reduction in generation from CCGT plants, while diesel generation gains importance.

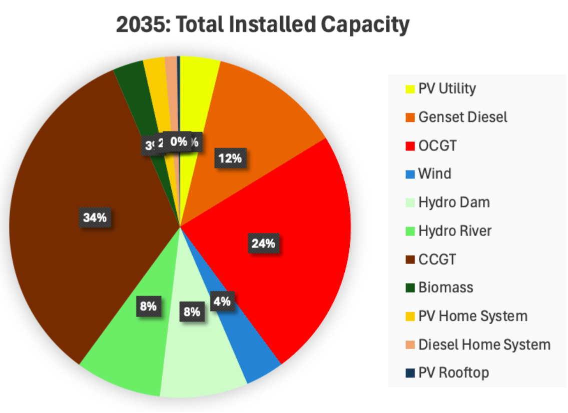

Figure 3.21: Installed capacity mix in 2035 after integrating all regions.

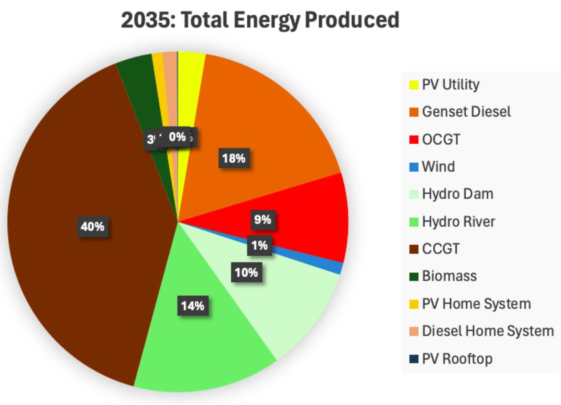

Figure 3.22: Electricity generation mix in 2035 after integrating all regions.

System-level impacts (costs, energy, emissions): Table 3.10 summarizes the main indicators for 2035. Remote regions account for about 3,17 % of system costs, 2,82 % of total electricity, and 0,025 % of emissions.

Table 3.10: Integration of remote regions into the national system (2035): system-level metrics.

	National total	Remote regions	Share [%]
System cost [M€]	1 242,22	39,41	3,17
Electricity [GWh]	13 393,77	377,99	2,82
Emissions [kt CO_2]	8 875,01	2,23	0,025

2050 Results

Modelling assumptions specific to 2050: For 2050, the public repository did not provide bounds for the existing Bolivian grid. To avoid arbitrary caps, we relaxed the upper bounds by referencing the country's technical potentials by technology [15]. Non-renewable technologies (gas, diesel) were left without explicit capacity limits, while renewables were bounded by their technical potentials: wind 250 GW, PV 40 000 GW, hydropower 39,9 GW, and biomass 850 MW. In addition, we preserved capacity continuity from 2035 to 2050 (commissioned assets remain available in 2050), which keeps the 2035 diesel fleet in the system even if its dispatch declines.

National mixes (2050): Figures 3.23 and 3.24 display the installed capacity and generation mixes for 2050 with all regions integrated. Relative to 2024–2035, the system shifts markedly towards hydropower once renewable ceilings are relaxed: hydropower supplies $>$ 90 % of annual electricity, reflecting its low variable cost and high availability within the explored potential. By contrast, diesel retains a noticeable share of installed capacity but produces very little energy. This residual diesel power stems from the 2035 build (capacity continuity), playing a back-up/adequacy role rather than a baseload source in 2050.

It is worth noting that, despite hydropower's dominance in generation, the model installs 2,24 GW of hydro in 2050, far below the technical potential bound of 39,9 GW.

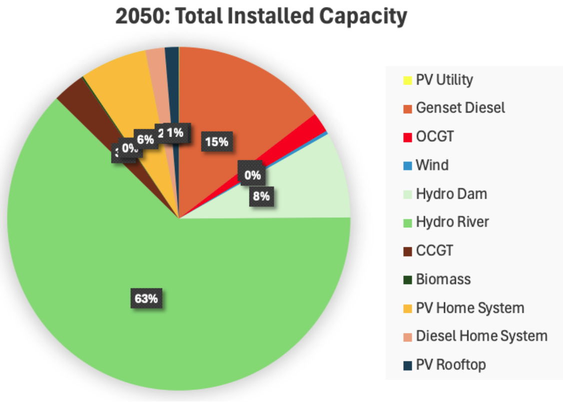

Figure 3.23: 2050 All Regions Capacity Mix

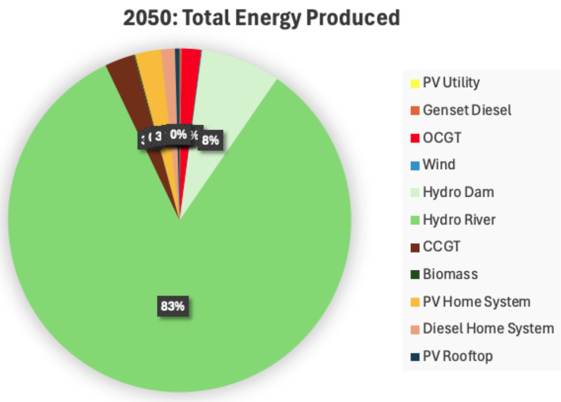

Figure 3.24: 2050 All regions Energy Mix

System-level impacts (costs, energy, emissions): Table 3.11 summarizes the aggregate indicators for 2050. Remote regions supply 4,38 % of national electricity but represent 8,54 % of total system costs; their direct CO_2 contribution remains negligible relative to the national total.

As observed, the contribution of remote communities to total system costs increases significantly. This is mainly due to the sharp reduction in overall costs driven by the large deployment of hydropower, which lowers total expenditures and, in proportion, makes the share of remote areas appear larger.

Table 3.11: Integration of remote regions into the national system (2050): system-level metrics.

	National total	Remote regions	Share [%]
System cost [M€]	694,09	59,28	8,54
Electricity [GWh]	12 292,26	538,60	4,38
Emissions [kt CO_2]	9.035,62	2,63	0,03

It is important to note that, despite the growing demand across all end-use categories, electricity production decreases in the 2050 scenario. This outcome is mainly explained by the model choosing to meet heating demand with fossil gas rather than electricity, as was the case in the previous simulation. This shift is illustrated in the Sankey diagram in Figure 3.25, while the comparison with the Sankey diagrams from earlier years is provided in Appendix B.

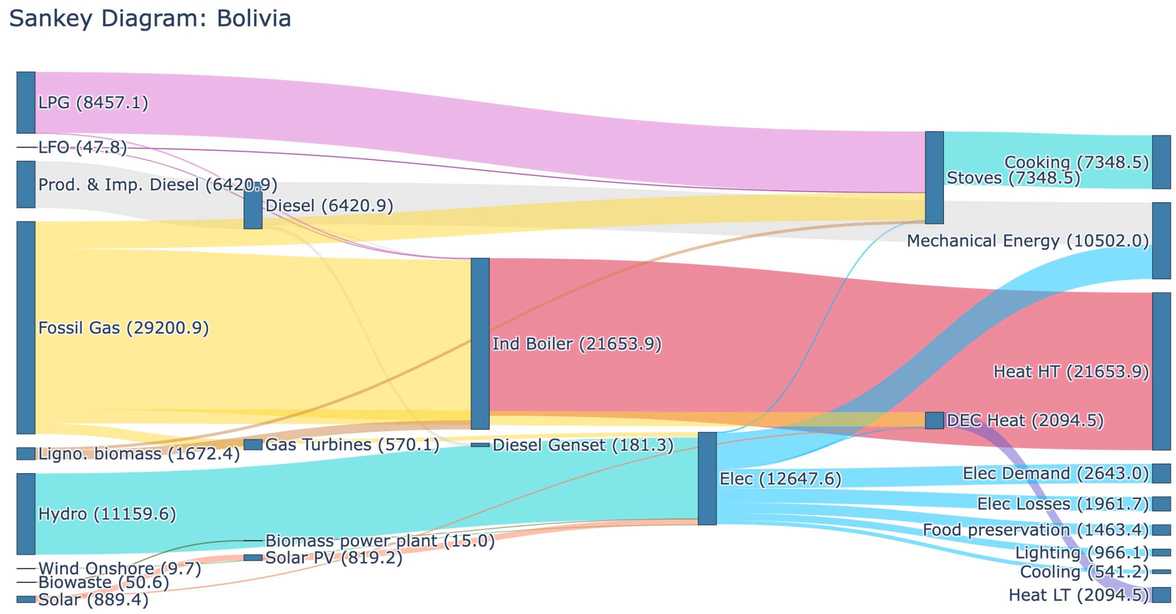

Figure 3.25: All regions 2050 Sankey Diagram

Emissions in 2050. As reported in Table 3.11, total emissions increase slightly in 2050 compared with earlier years. This does not contradict the largely renewable electricity mix: the rise is driven by non-electric demands,space and water heating, cooking, and mechanical energy—which the model still supplies mainly with fossil fuels. The all-Bolivia Sankey in Figure 3.25 makes this split clear: most electricity comes from hydropower, while thermal and mechanical energy flows remain mostly non-renewable. The power sector is low-carbon, but decarbonization of non-electric demands is still pending, which explains the modest rise in total emissions.

3.2.3 All-Bolivia comparison across years (2024–2035–2050)

This subsection summarizes national outcomes across snapshots and the incremental role of remote regions. Table 3.12 reports, side by side, system costs, electricity, and emissions for Bolivia as a whole and for remote regions, including their percentage contribution.

Table 3.12: System-level metrics by year: national totals vs. remote regions.

Year	Metric	National total	Remote regions	Share [%]
2024	System cost [M€]	805,59	31,31	3,89
	Electricity [GWh]	11 198,95	317,40	2,83
	Emissions [kt CO_2]	8 239,59	0,919	0,011
2035	System cost [M€]	1 242,22	39,41	3,17
	Electricity [GWh]	13 393,77	377,99	2,82
	Emissions [kt CO_2]	8 875,01	2,23	0,025
2050	System cost [M€]	694,09	59,28	8,54
	Electricity [GWh]	12 292,26	538,60	4,38
	Emissions [kt CO_2]	9 035,62	2,63	0,03

Source: Tables 4.9 (2024), 4.10 (2035) and 4.11 (2050).

Table 3.13 presents the cost-to-energy share ratio for remote regions. In 2024 and 2035 it lies between 1,12 and 1,37, meaning remote areas account for a larger share of costs than of electricity. This reflects higher unit costs to serve dispersed and off-grid demand.

In 2050 the ratio rises to 1,95. This reflects two effects: national system costs fall as hydropower dominates generation, while remote supply remains largely decentralised, with Home Systems providing most of the energy and incurring higher per-unit costs than conventional grid options. Thus, even as the electricity share of remote regions grows, their relative cost contribution increases more sharply.

Table 3.13: New Regions Cost/Energy share ratio

Indicator	2024	2035	2050
Remote cost / energy share ratio	1,37	1,12	1,95

3.3 Discussion

Demand (RAMP): The RAMP simulations provide disaggregated electricity demands by end-use and by region. Thermal applications dominate the profiles, most notably water heating and cold storage, while the regional patterns align with the expected climatic differences. The average annual electricity use estimated for remote communities is about 866 kWh per inhabitant, which is of the same order as the current national average in Bolivia (948,9 kWh per inhabitant reported earlier), and therefore plausible in these contexts.

Remote regions in isolation: In the initial year, electricity demand is supplied predominantly by Diesel Home Systems, followed by PV Home Systems. Other renewable sources play a secondary role. Storage is dimensioned mainly to smooth short-term fluctuations rather than to provide multi-hour or multi-day autonomy. The simulations also satisfy the minimum Home System requirement imposed by the model. Once this threshold is met, the remaining demand is covered by additional renewables, primarily wind, followed by rooftop PV and biomass. Over time, as the minimum-capacity restriction applied in 2024 is lifted, PV becomes the main source of electricity and the installed battery capacity increases accordingly. The introduction of modern cooking technologies, especially LPG, proves more effective in the system than the initial biomass options.

System-wide perspective and 2050: By 2050, Bolivia's renewable potential highlights the importance of integrating remote regions into the national grid so they can benefit from low-cost hydropower. Otherwise, proportional costs for remote supply increase markedly. While Home Systems offer a pragmatic solution in the near term for sparsely populated areas, they become comparatively costly once the grid advances towards lower-cost generation options.

Implications: In the early years, remote areas can satisfy their electricity needs mainly through Home Systems because population density is insufficient to justify grid extension. This remains viable for a period, with somewhat higher costs than the national average. However, as Bolivia unlocks its renewable potential, the relative cost of standalone solutions grows significantly. Looking forward, national planning for remote communities should explicitly prioritise their integration into an interconnected electricity network, whether via the existing SIN/SA systems or through appropriately sized new microgrids, so that less expensive generation technologies can be used at scale.

4. Conclusions and Further Work

4.1 Conclusions

Throughout this thesis, a non-conventional workflow was applied. First, bottom-up stochastic electricity-demand profiles were generated to characterise remote communities without grid connection, populations typically omitted from national planning. These profiles were then integrated into the national EnergyScope MultiCell model to assess system-level impacts and identify feasible supply portfolios to meet their requirements. In doing so, unelectrified regions became explicitly represented within national planning. Overall, the objectives were met: demands were constructed, integrated, and analysed within a coherent workflow that links demand synthesis with national optimisation.

Contributions: Beyond its analytical results, this thesis delivers two practical contributions. First, on the demand side, it assembles a reusable set of RAMP inputs covering households, community services, and income-generating activities, disaggregated by region (Highlands, Valleys, Lowlands). This library can be redeployed in other Bolivian contexts to support comparative studies. Second, on the planning side, it operationalises the representation of remote communities in EnergyScope MultiCell by adding dedicated cells, implementing the necessary constraints, and introducing new equations to accommodate the additional technologies, enabling future studies to account for unelectrified areas within a unified national framework and thereby improving the model's coverage and fidelity.

Results: Once the demand profiles for the unelectrified macro-regions were generated, clear inter-regional differences emerged, largely driven by climate. Moreover, adopting a bottom-up approach based on appliance-specific inputs for each type of infrastructure enabled the generation of stochastic demand curves with minute-level resolution across the year, and the resulting magnitude of these demands proved reasonable when compared with current Bolivian benchmarks. Integrating these demands into the national EnergyScope MultiCell model delivered scenario results for 2024, 2035, and 2050: unelectrified regions supplied approximately 2,8%–4,4% of Bolivia's total electricity once integrated, while accounting for roughly 3,2%–8,5% of total system costs. This disparity indicates a higher cost per kWh for remote electrification.

In terms of technology choice, the optimisations consistently selected PV coupled with short-duration storage as the backbone for remote supply, complemented by backup generation to ensure adequacy. Early scenarios relied more on Diesel Home Systems, but the share of PV-based HS with batteries grew steadily and, by 2050, overtook diesel within the remote portfolios.

Final conclusion: The results support a staged pathway to rural electrification in Bolivia. In the near term, deploying stand-alone Home Systems is a sound solution to meet rural electricity needs, offering rapid, practical access for dispersed communities. As Bolivia progressively harnesses its substantial renewable potential and system-wide costs decline, the preferred strategy should shift toward gradually integrating communities into the national grid, thereby allowing them to benefit from the lower costs of large-scale renewable technologies.

4.2 Limitations

The study presents several limitations that should be acknowledged. Grid-extension costs and mobility in remote regions were excluded from the optimisation baseline, which could affect the balance between off-grid and interconnected solutions. Hydropower availability was represented with simplified bounds, overlooking ecological and seasonal constraints that might reduce its dominance in the 2050 mix. Remote demand was aggregated into three macro-regions, potentially masking heterogeneity in costs, resources, and grid-connection feasibility at finer spatial scales. Finally, although additional scenarios were initially planned, particularly a 2050 decarbonisation case, these could not be implemented due to technical issues and time limitations.

4.3 Further work

- **Richer demand modelling:** Move from seasonal to monthly (or higher) resolution; expand surveys and appliance libraries; include public and private mobility in remote areas.
- **Net-zero scenarios:** Add explicit emission caps or price trajectories to explore decarbonisation pathways to 2050, resolving the technical issues encountered with emission constraints.
- **Hydro realism:** Impose seasonal inflows and eco-hydrological limits to bound hydro dispatch and test portfolios if hydro availability tightens.
- **Finer regional segmentation:** Subdivide the three macro-regions used in this thesis into smaller subregions to obtain more realistic results by better capturing heterogeneity in costs, resources, and connection options.
- **Integration of remote communities into the grid:** As Bolivia's renewable potential is exploited and national system costs fall, the relative cost of standalone remote supply increases. Prioritise the progressive integration of remote areas into the national electricity grid where feasible.

A. RAMP Plots

This appendix compiles the demand profiles produced by the RAMP framework for each region and end-use group. For each case, we report: (i) the mean daily profile, (ii) the full-year profile, and (iii) the load duration curve (LDC).

A.1 Highlands (HL)

A.1.1 Community Services

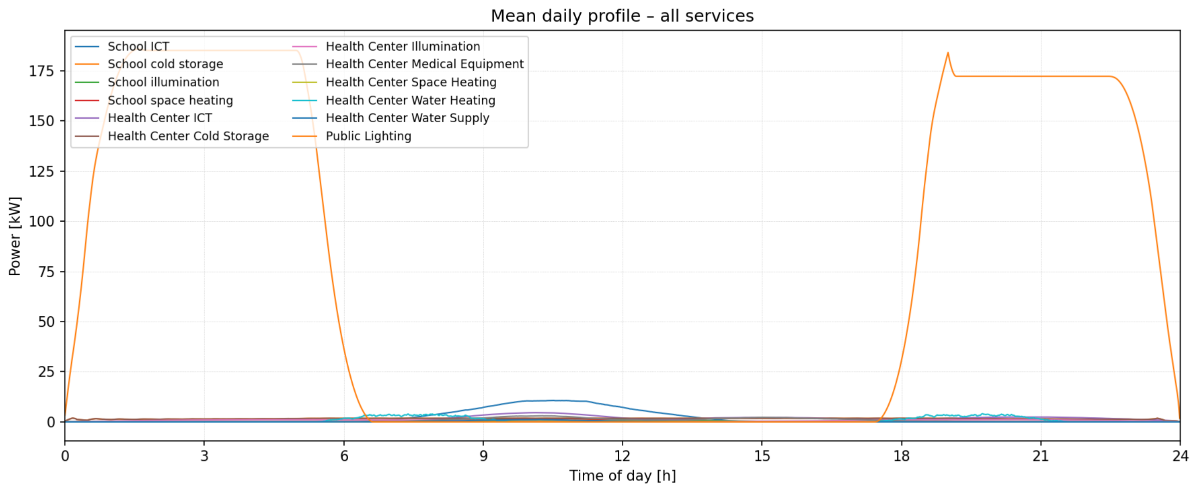

Figure A.1: Mean daily demand profiles for Community Services in the Highlands (HL).

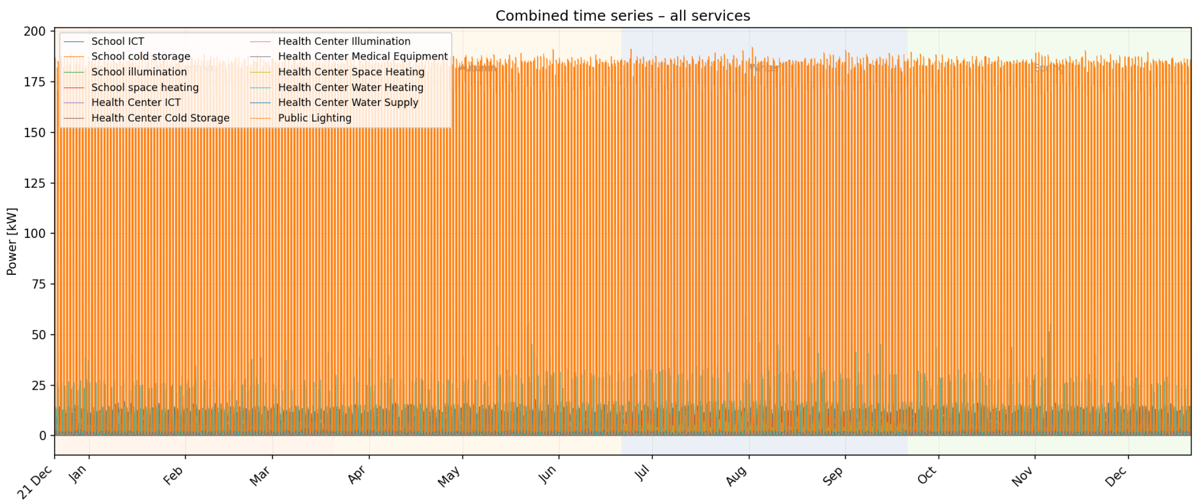

Figure A.2: Full-year demand profile for Community Services in the Highlands (HL).

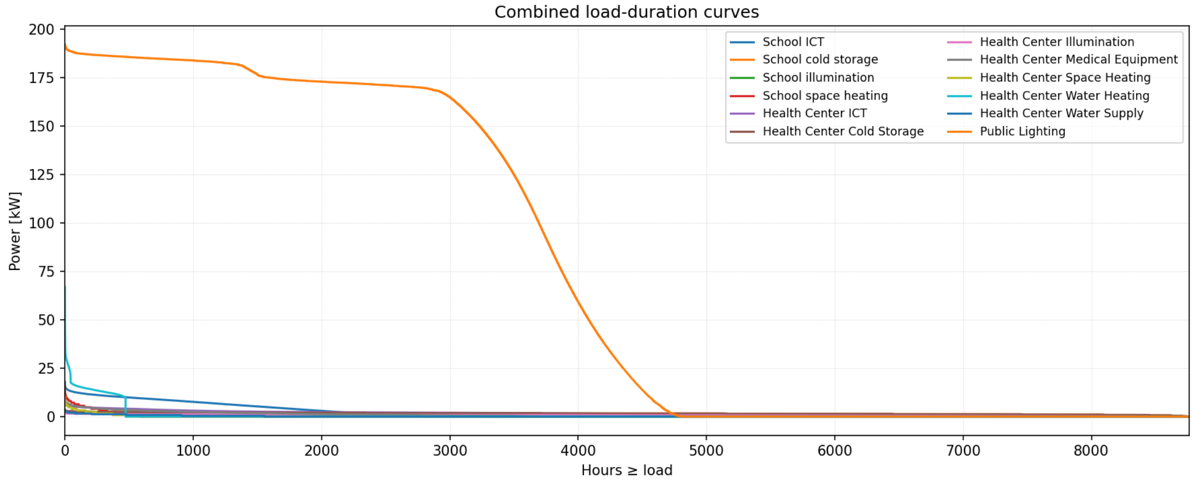

Figure A.3: Load Duration Curve (LDC) for Community Services in the Highlands (HL).

A.1.2 Households

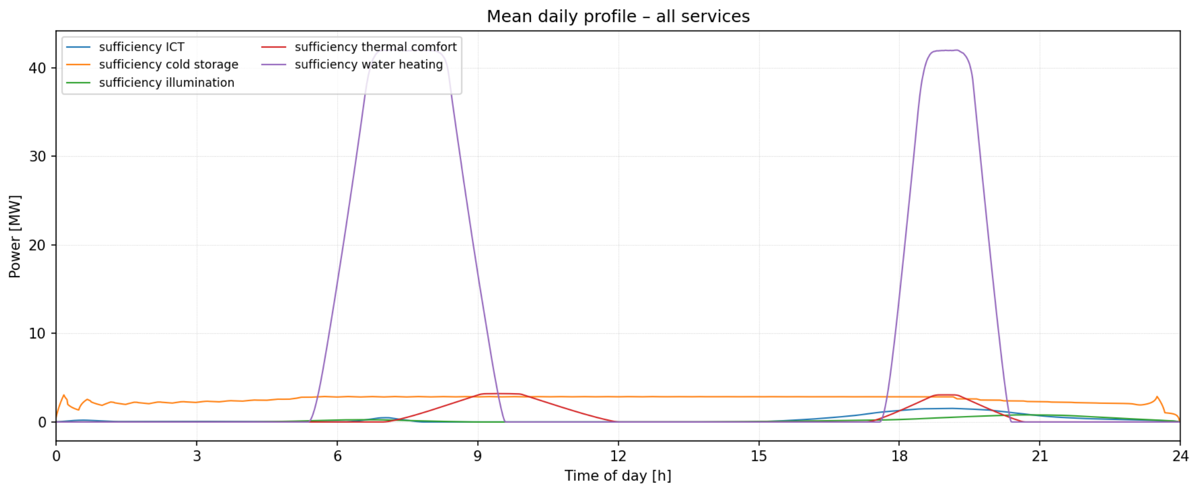

Figure A.4: Mean daily demand profiles for Households in the Highlands (HL).

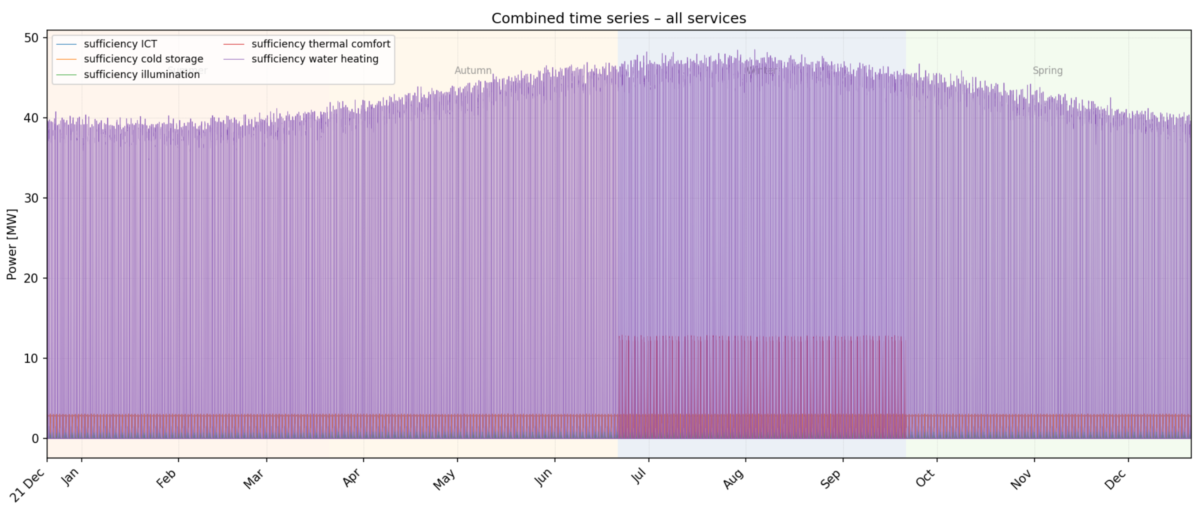

Figure A.5: Full-year demand profile for Households in the Highlands (HL).

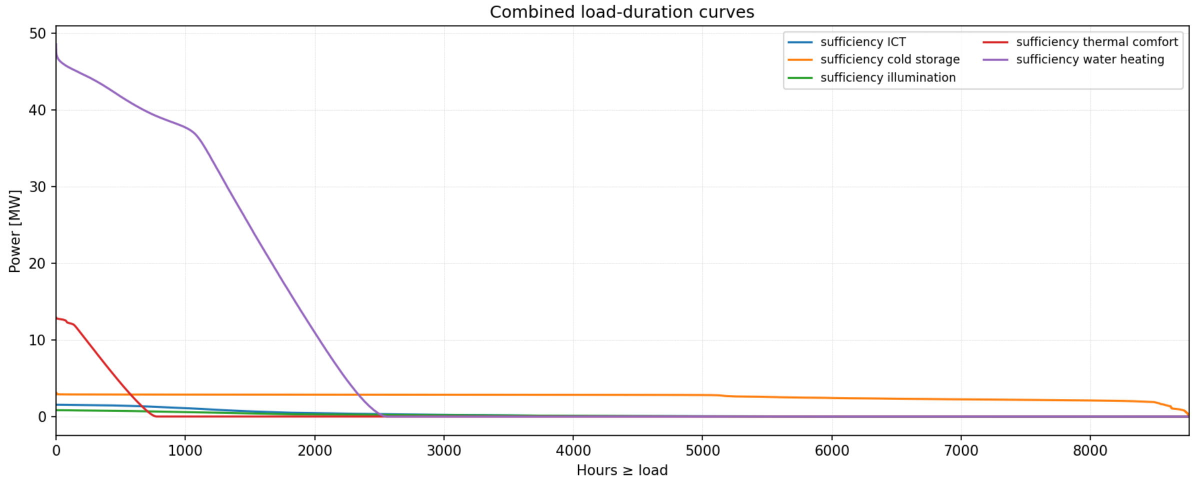

Figure A.6: Load Duration Curve (LDC) for Households in the Highlands (HL).

A.1.3 IGAs

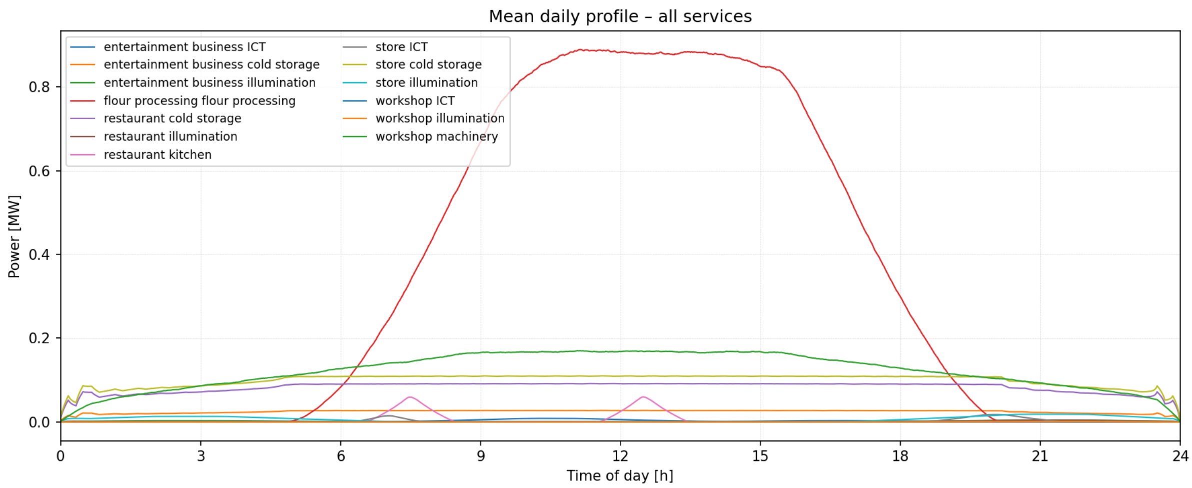

Figure A.7: Mean daily demand profiles for IGAs in the Highlands (HL).

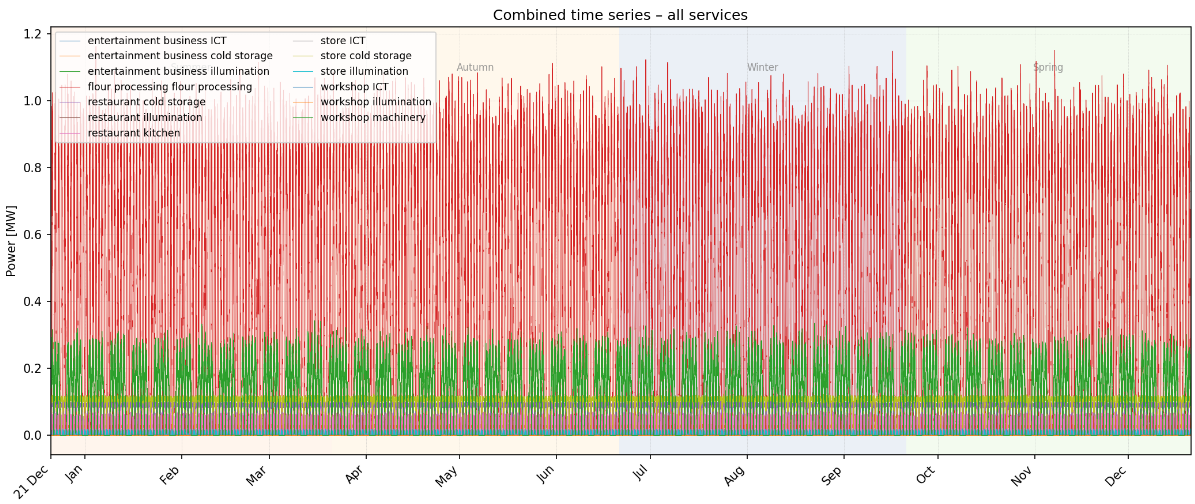

Figure A.8: Full-year demand profile for IGAs in the Highlands (HL).

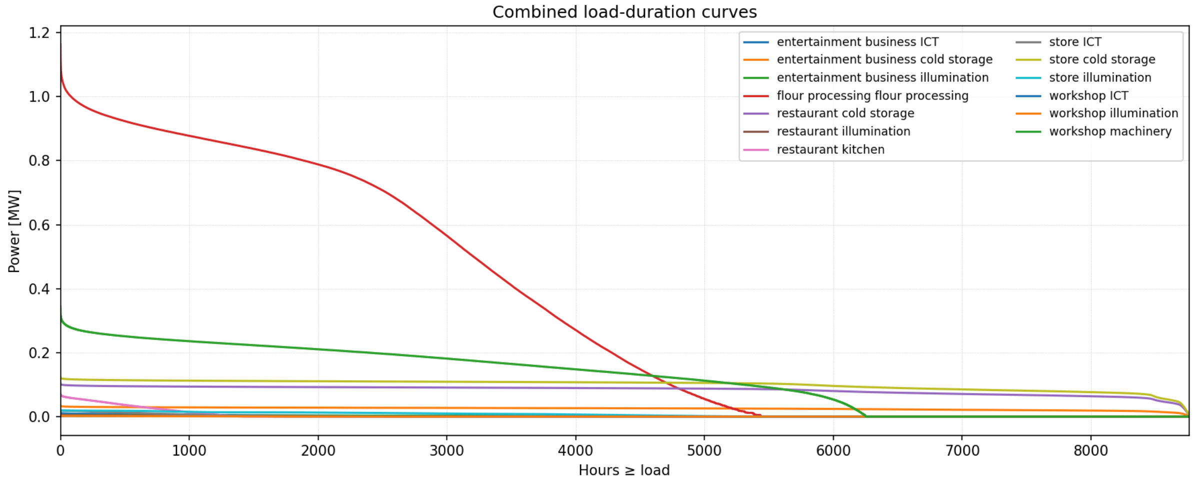

Figure A.9: Load Duration Curve (LDC) for IGAs in the Highlands (HL).

A.2 Lowlands (LL)

A.2.1 Households

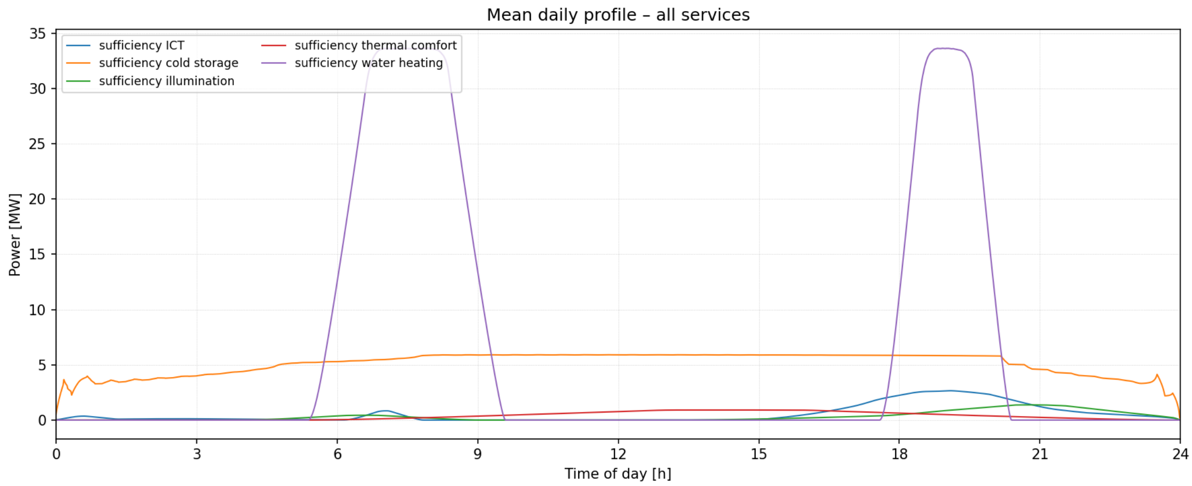

Figure A.10: Mean daily demand profiles for Households in the Lowlands (LL).

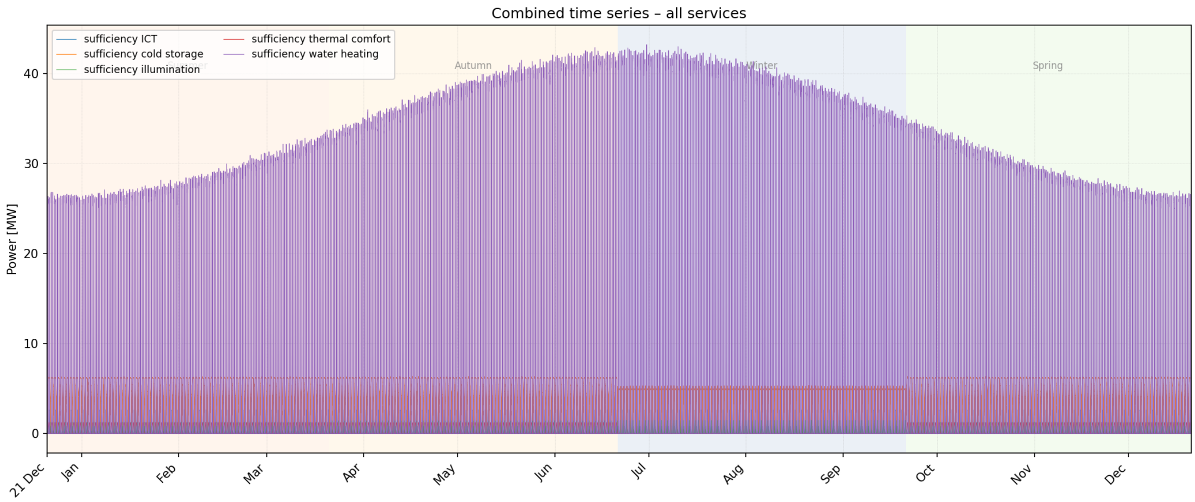

Figure A.11: Full-year demand profile for Households in the Lowlands (LL).

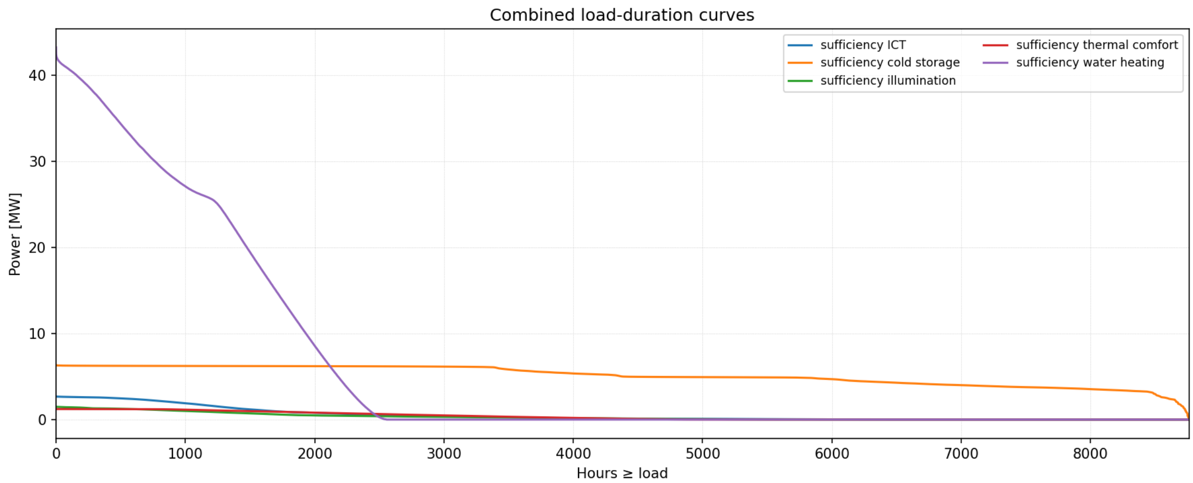

Figure A.12: Load Duration Curve (LDC) for Households in the Lowlands (LL).

A.2.2 IGAs

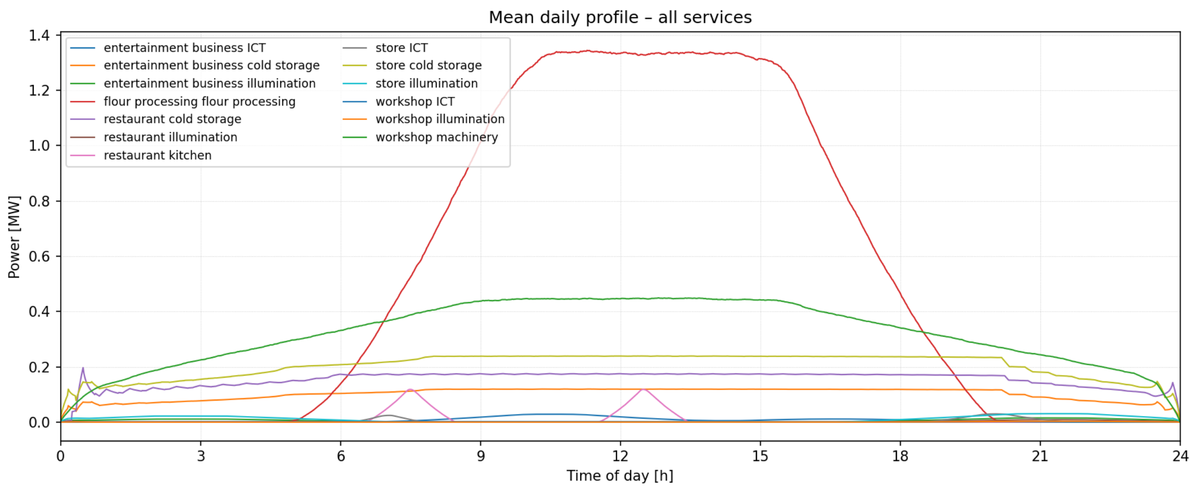

Figure A.13: Mean daily demand profiles for IGAs in the Lowlands (LL).

Figure A.14: Full-year demand profile for IGAs in the Lowlands (LL).

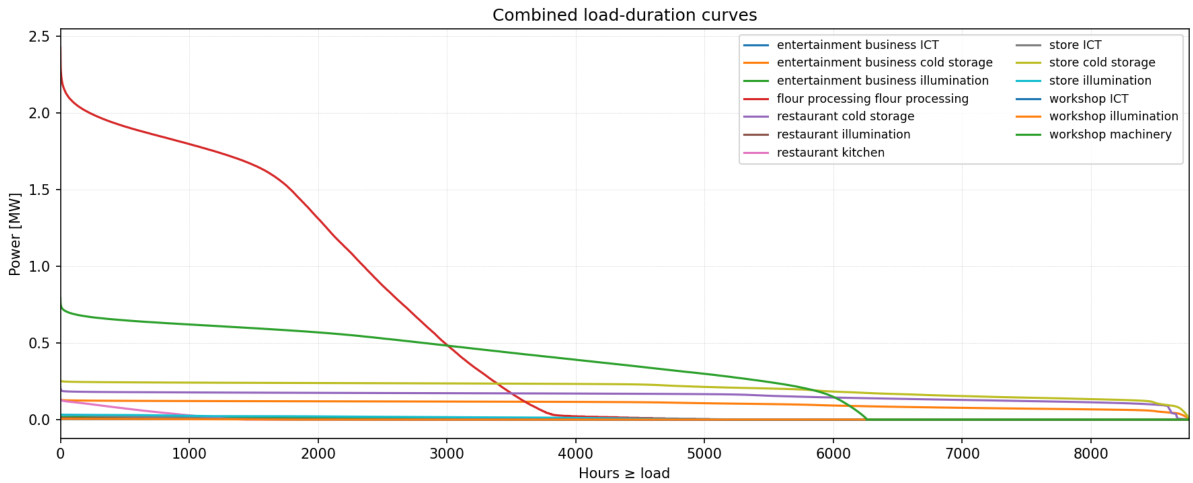

Figure A.15: Load Duration Curve (LDC) for IGAs in the Lowlands (LL).

A.2.3 Community Services

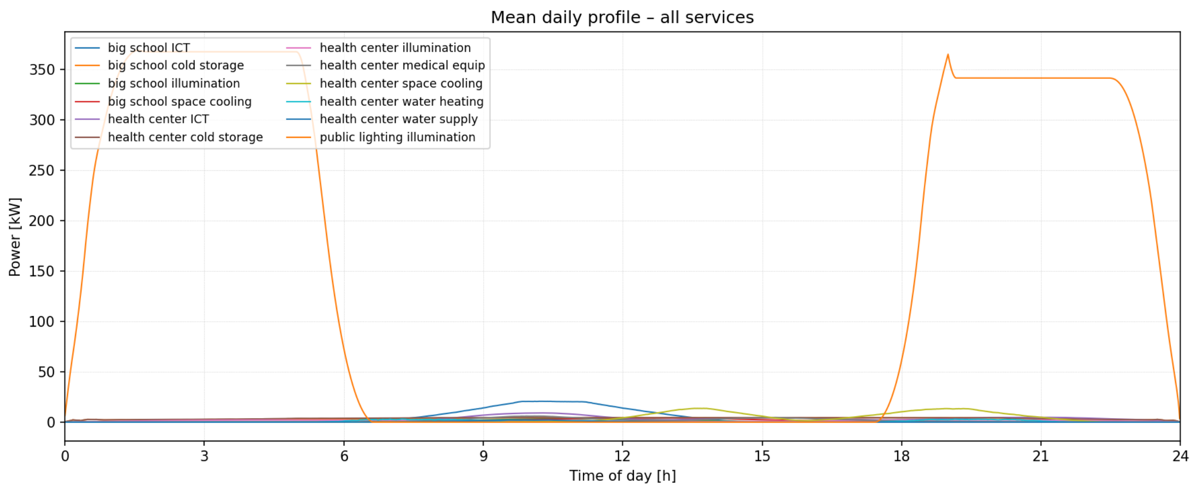

Figure A.16: Mean daily demand profiles for Community Services in the Lowlands (LL).

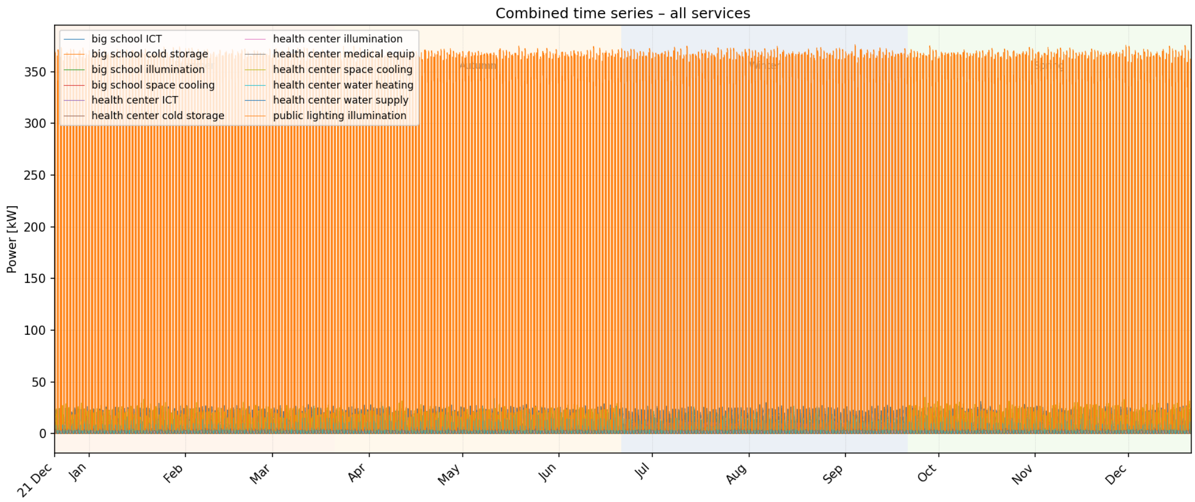

Figure A.17: Full-year demand profile for Community Services in the Lowlands (LL).

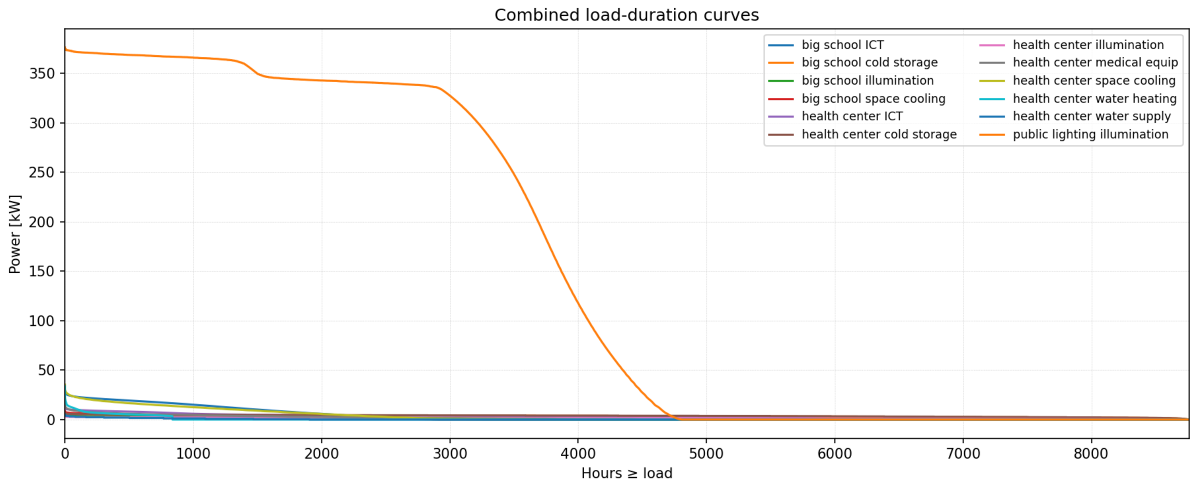

Figure A.18: Load Duration Curve (LDC) for Community Services in the Lowlands (LL).

A.3 Valleys (VL)

A.3.1 Households

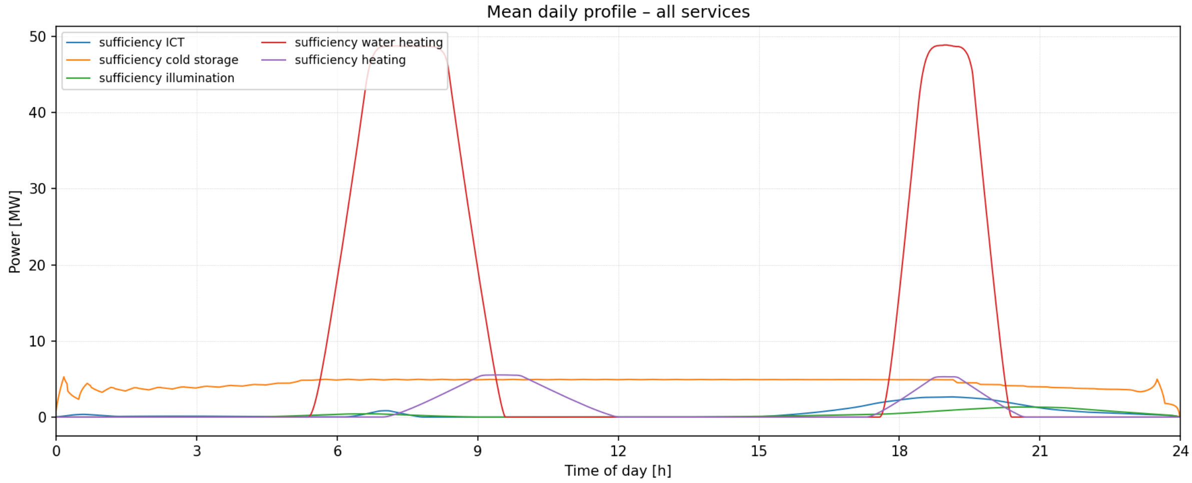

Figure A.19: Mean daily demand profiles for Households in the Valleys (VL).

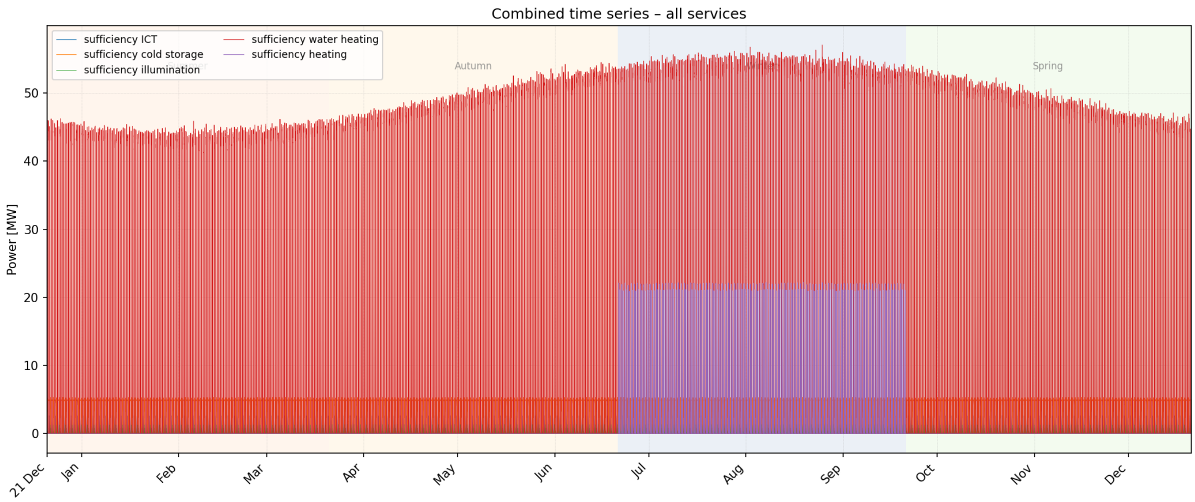

Figure A.20: Full-year demand profile for Households in the Valleys (VL).

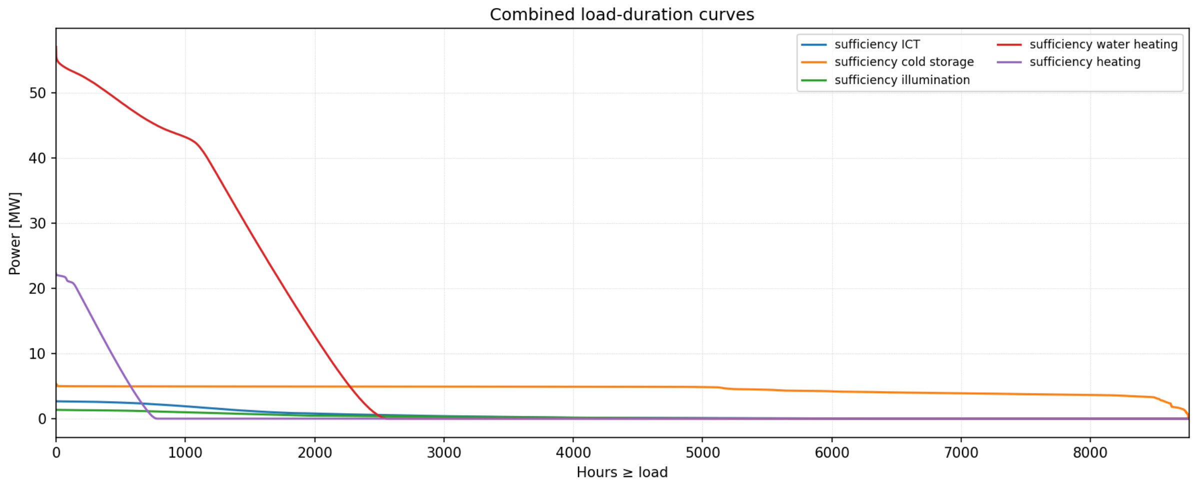

Figure A.21: Load Duration Curve (LDC) for Households in the Valleys (VL).

A.3.2 IGAs

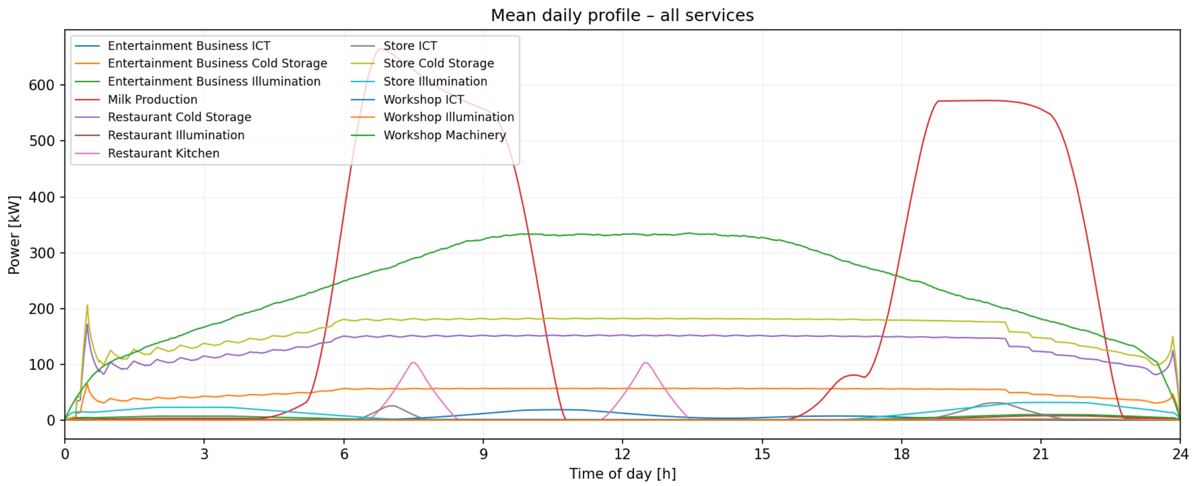

Figure A.22: Mean daily demand profiles for IGAs in the Valleys (VL).

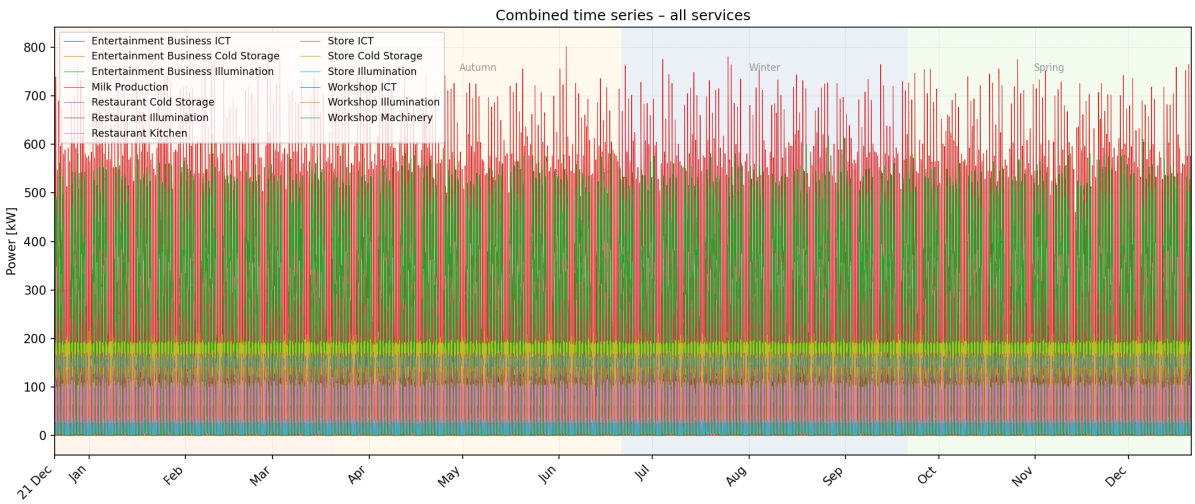

Figure A.23: Full-year demand profile for IGAs in the Valleys (VL).

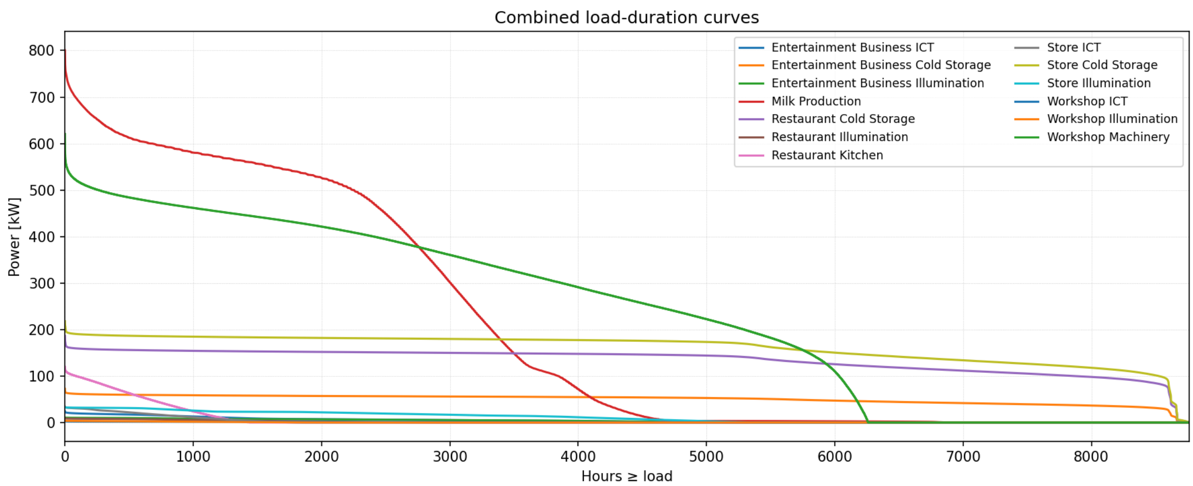

Figure A.24: Load Duration Curve (LDC) for IGAs in the Valleys (VL).

A.3.3 Community Services

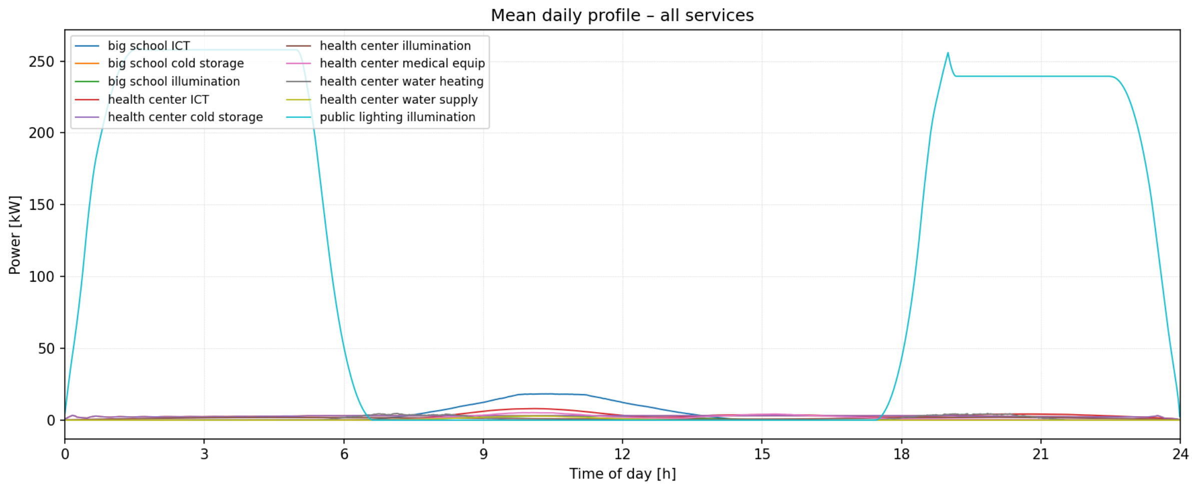

Figure A.25: Mean daily demand profiles for Community Services in the Valleys (VL).

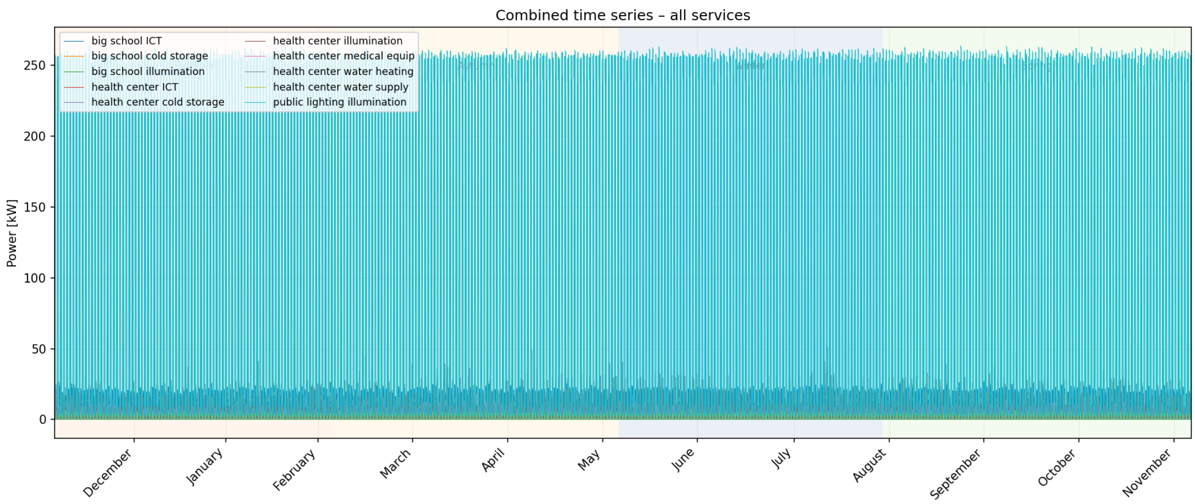

Figure A.26: Full-year demand profile for Community Services in the Valleys (VL).

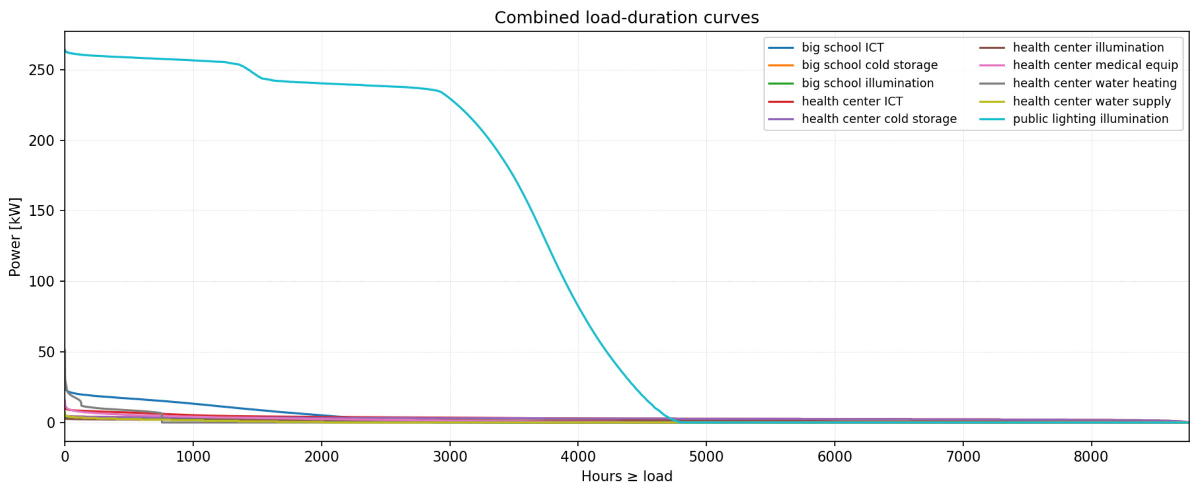

Figure A.27: Load Duration Curve (LDC) for Community Services in the Valleys (VL).

A.4 Cross-regional Comparison

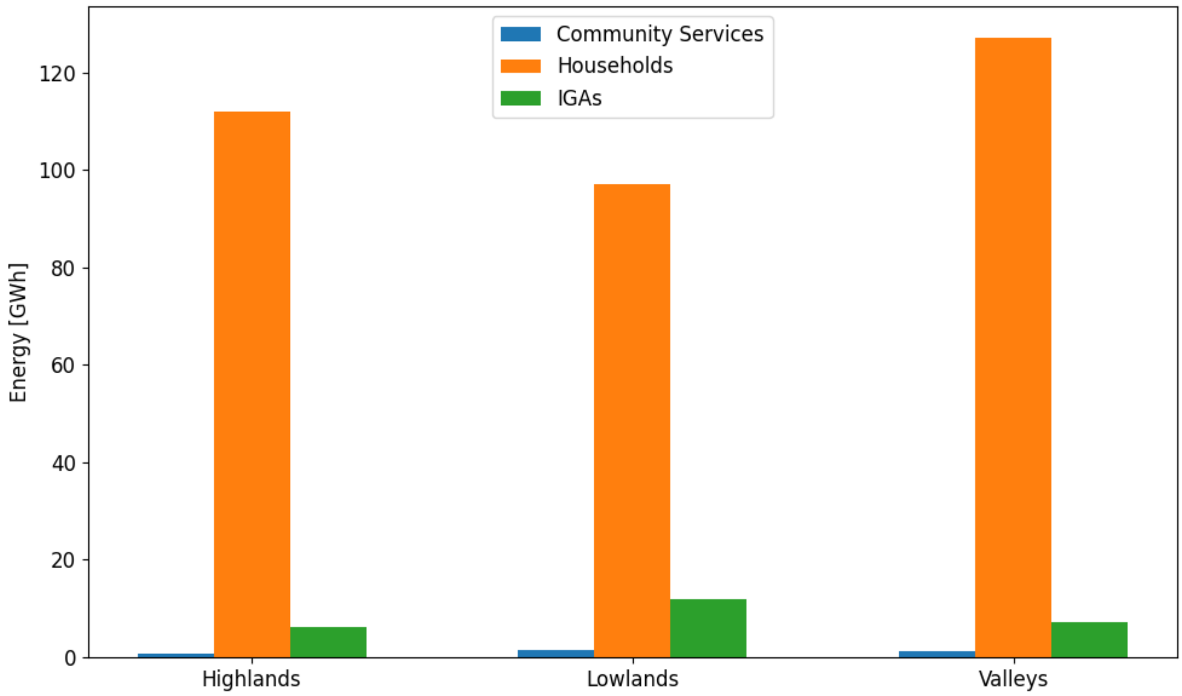

Figure A.28: Total annual electricity demand by sector for each Bolivian region.

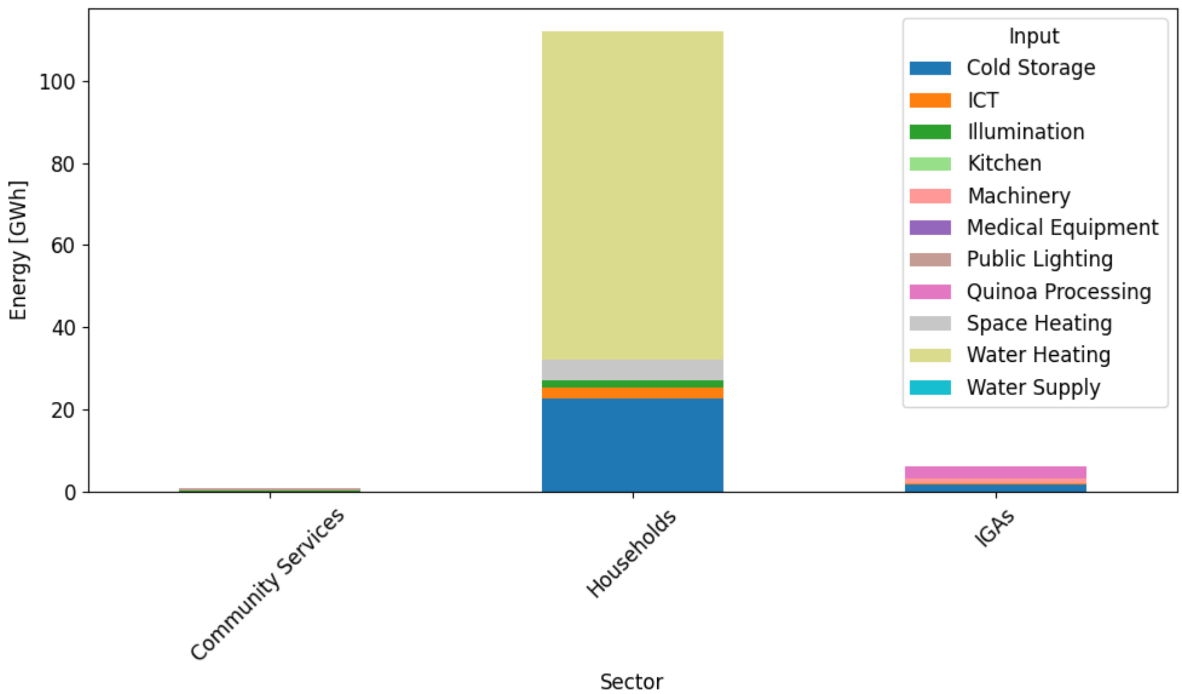

Figure A.29: Breakdown of annual electricity demand by input in the Highlands region.

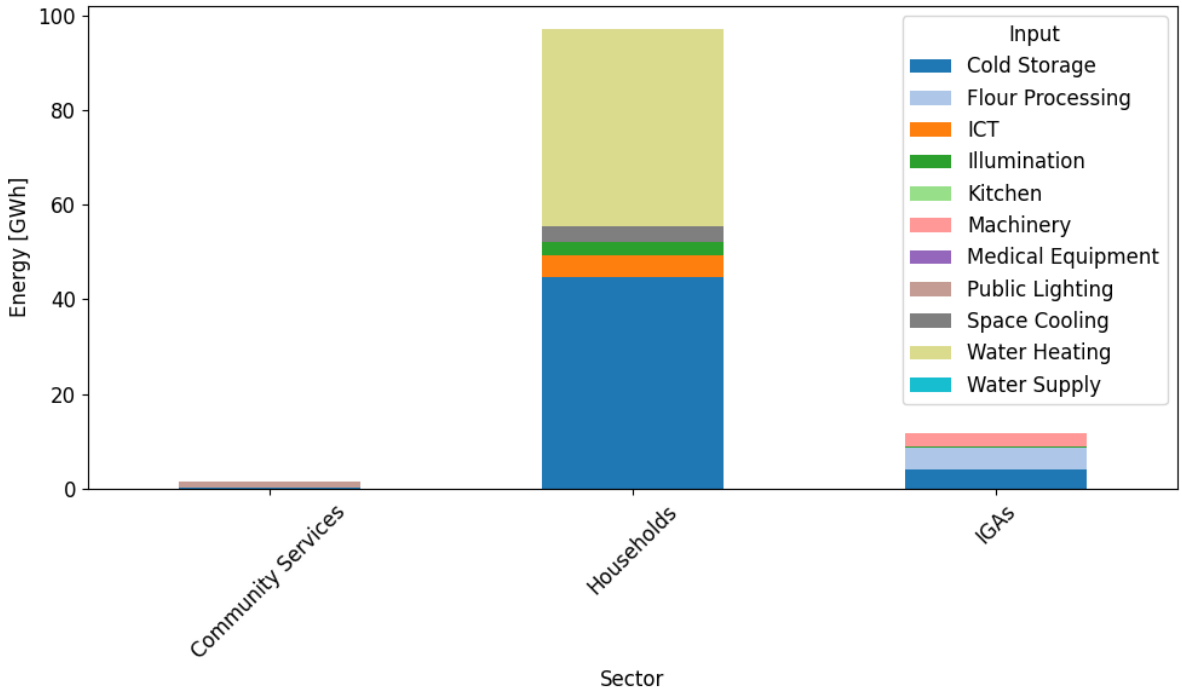

Figure A.30: Breakdown of annual electricity demand by input in the Lowlands region.

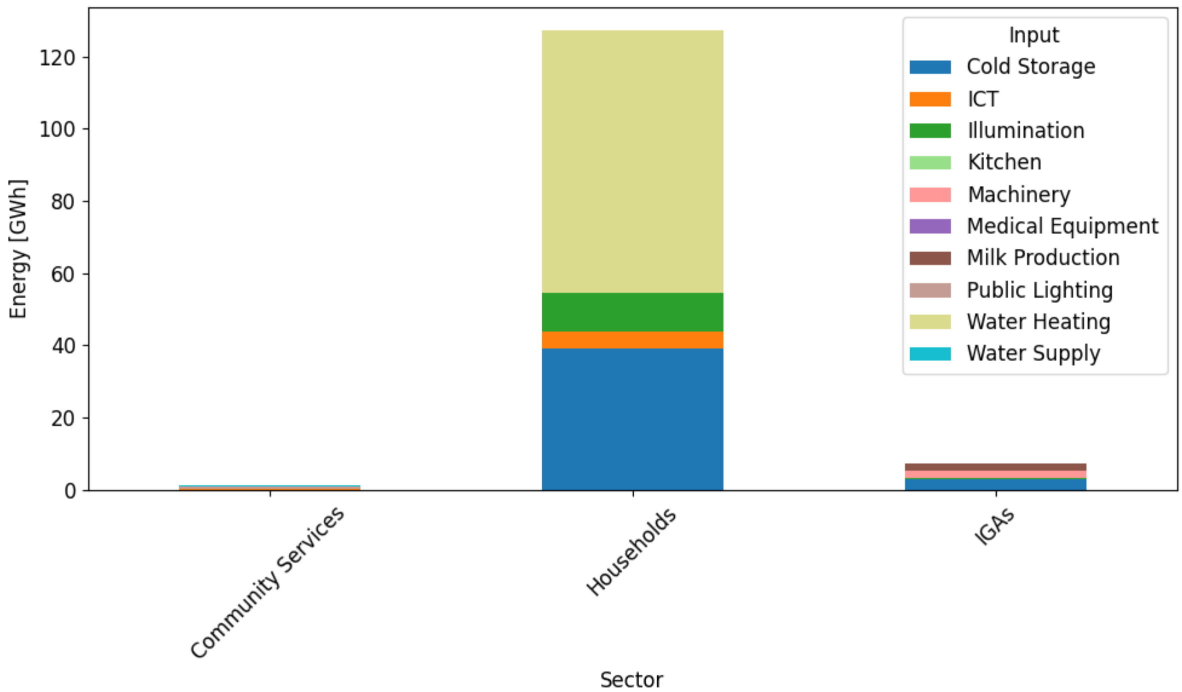

Figure A.31: Breakdown of annual electricity demand by input in the Valleys region.

Table A.1: Annual electricity demand by input and region (RAMP results). Values in GWh and regional shares (%).

Input	Highlands [GWh]	Highlands [%]	Lowlands [GWh]	Lowlands [%]	Valleys [GWh]	Valleys [%]
Water Heating	79,94	67,24	41,84	37,87	72,60	53,55
Cold Storage	24,50	20,61	48,76	44,13	42,22	31,14
Illumination	1,67	1,41	2,90	2,63	11,07	8,17
ICT	2,76	2,32	4,80	4,34	4,77	3,51
Thermal Comfort	5,19	4,37	3,26	2,95	0,00	0,00
Machinery	1,07	0,90	2,82	2,55	2,10	1,55
Flour Processing	0,00	0,00	4,64	4,20	0,00	0,00
Quinoa Processing	3,04	2,56	0,00	0,00	0,00	0,00
Public Lighting	0,67	0,57	1,34	1,21	0,94	0,69
Milk Production	0,00	0,00	0,00	0,00	1,81	1,34
Kitchen	0,04	0,03	0,08	0,07	0,07	0,05
Space Cooling	0,00	0,00	0,04	0,03	0,00	0,00
Medical Equipment	0,01	0,01	0,01	0,01	0,01	0,01
Water Supply	0,00	0,00	0,00	0,00	0,00	0,00

B. Sankey Diagrams

This appendix presents the complete set of Sankey diagrams generated during the analysis. They illustrate the energy flows and technological choices across the different years. All diagrams are shown separately.

B.1 Remote communities

B.1.1 2024 Results

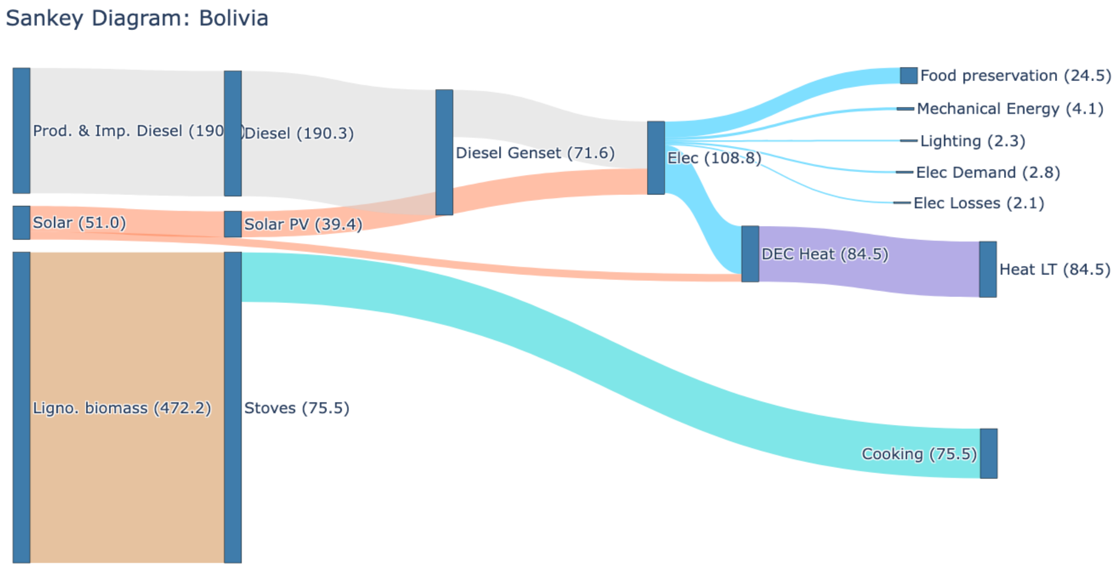

Figure B.1: Energy flow Sankey for Highlands (HL), 2024.

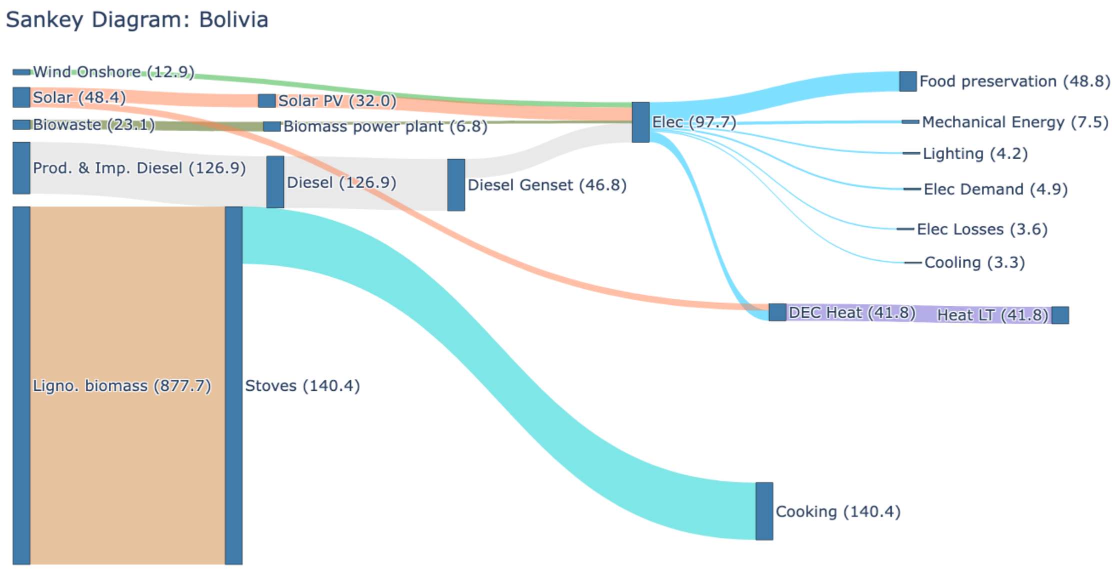

Figure B.2: Energy flow Sankey for Lowlands (LL), 2024.

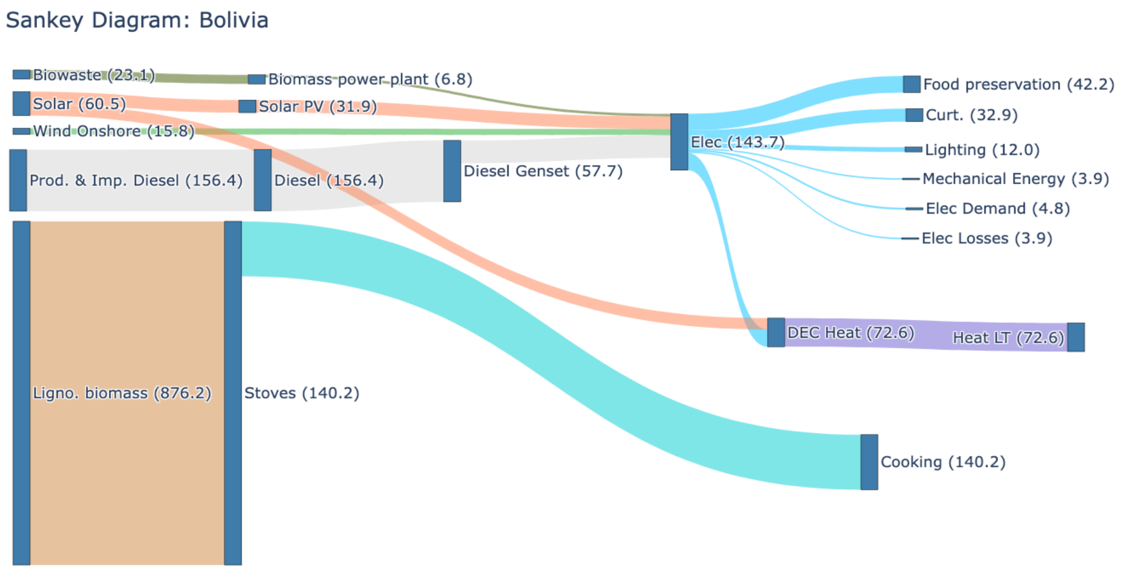

Figure B.3: Energy flow Sankey for Valleys (VL), 2024.

B.1.2 2035 Results

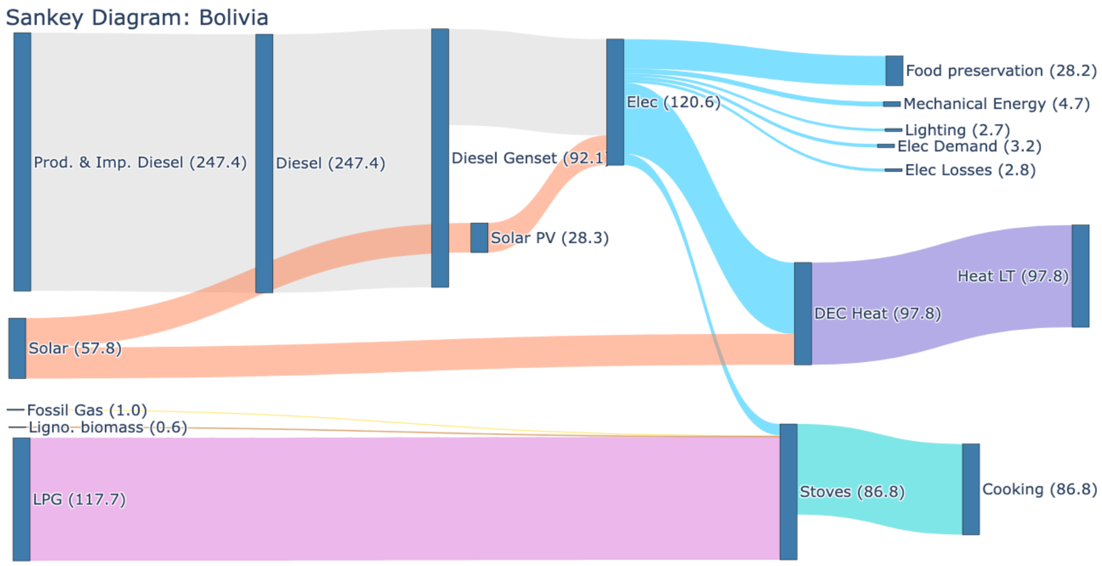

Figure B.4: Energy flow Sankey for Highlands (HL), 2035 scenario.

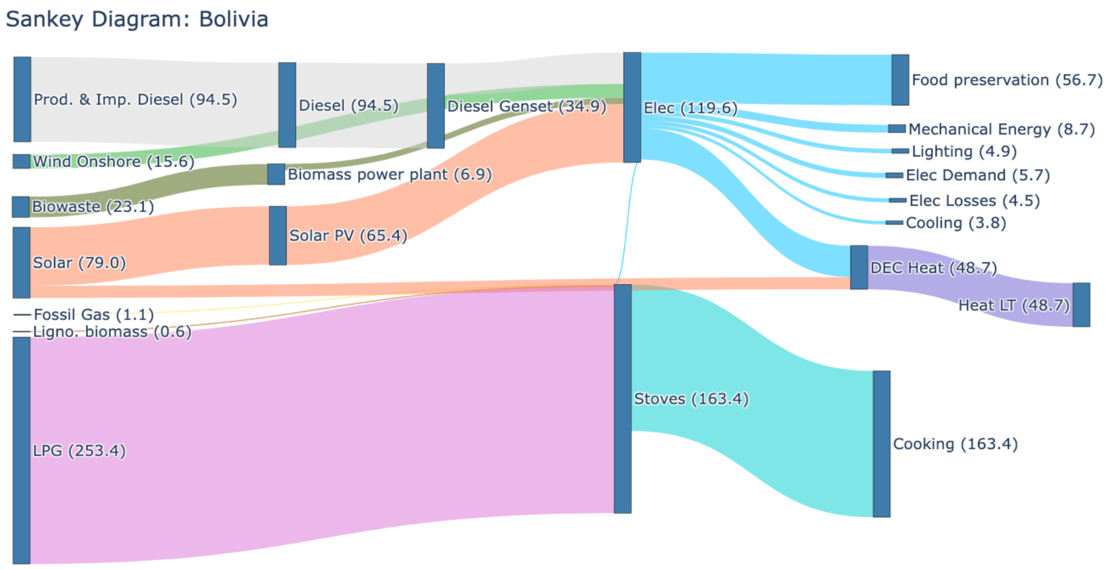

Figure B.5: Energy flow Sankey for Lowlands (LL), 2035 scenario.

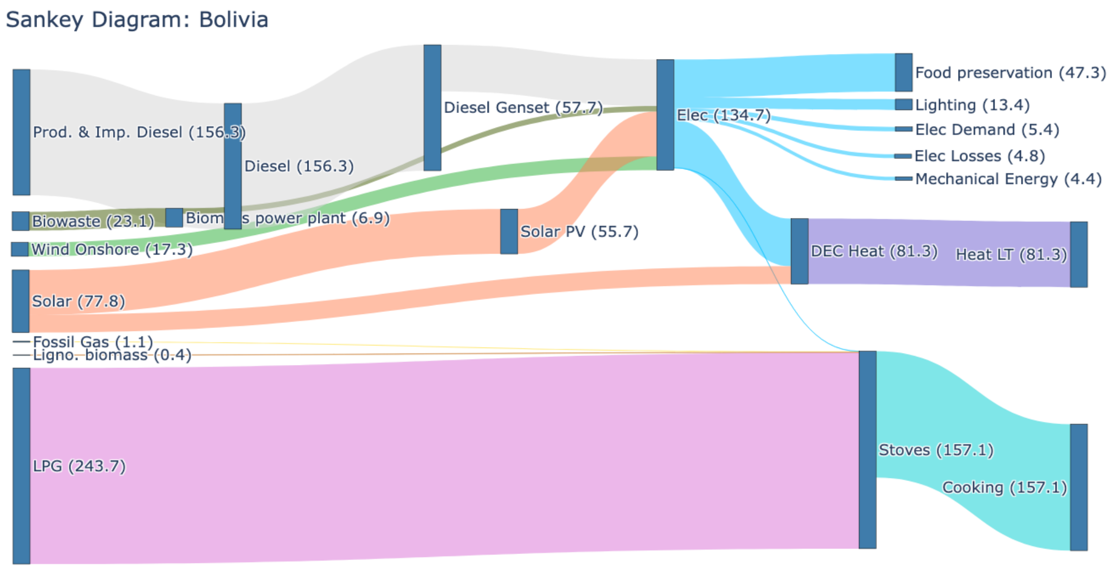

Figure B.6: Energy flow Sankey for Valleys (VL), 2035 scenario.

B.1.3 2050 Results

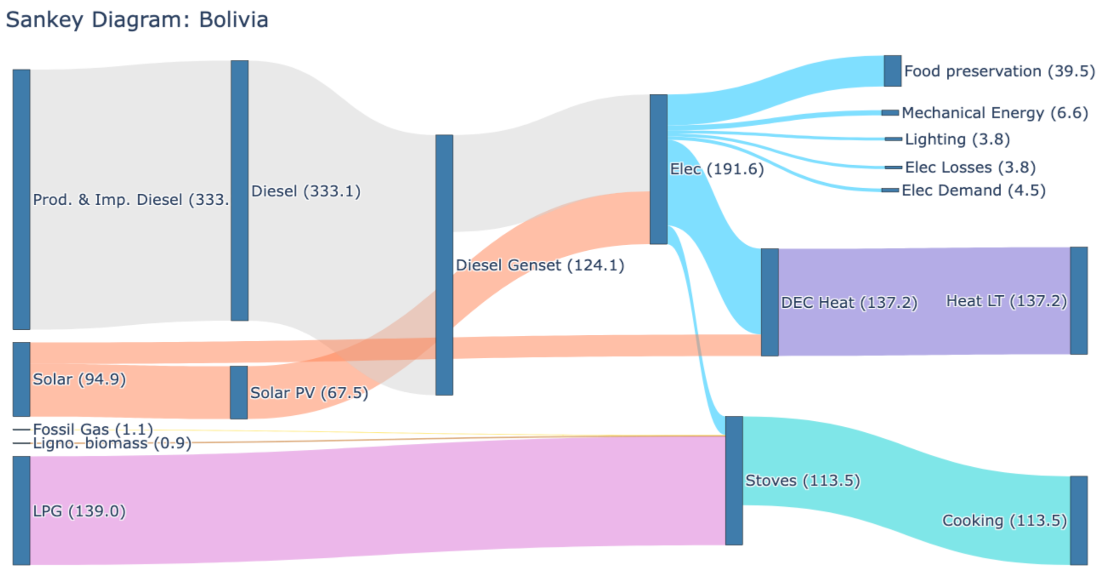

Figure B.7: Energy flow Sankey for Highlands (HL), 2050 scenario.

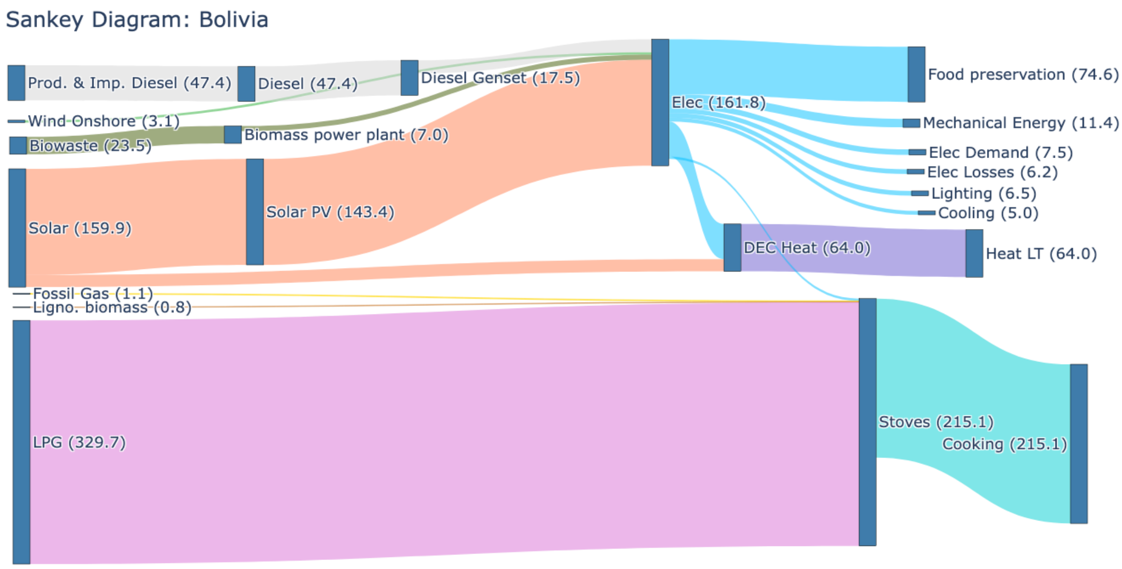

Figure B.8: Energy flow Sankey for Lowlands (LL), 2050 scenario.

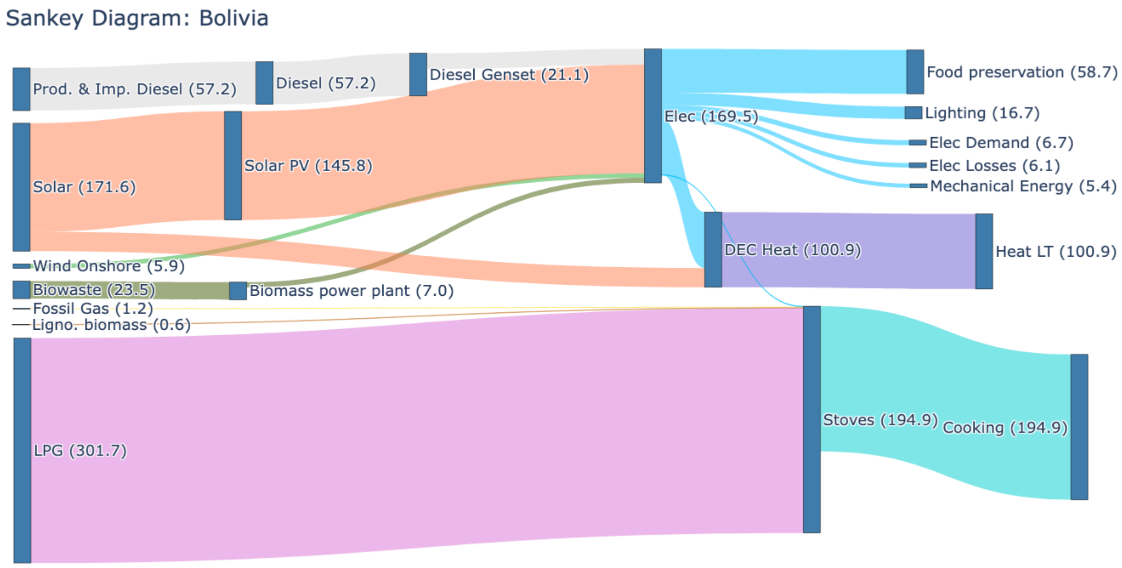

Figure B.9: Energy flow Sankey for Valleys (VL), 2050 scenario.

B.2 Results with remote communities integrated

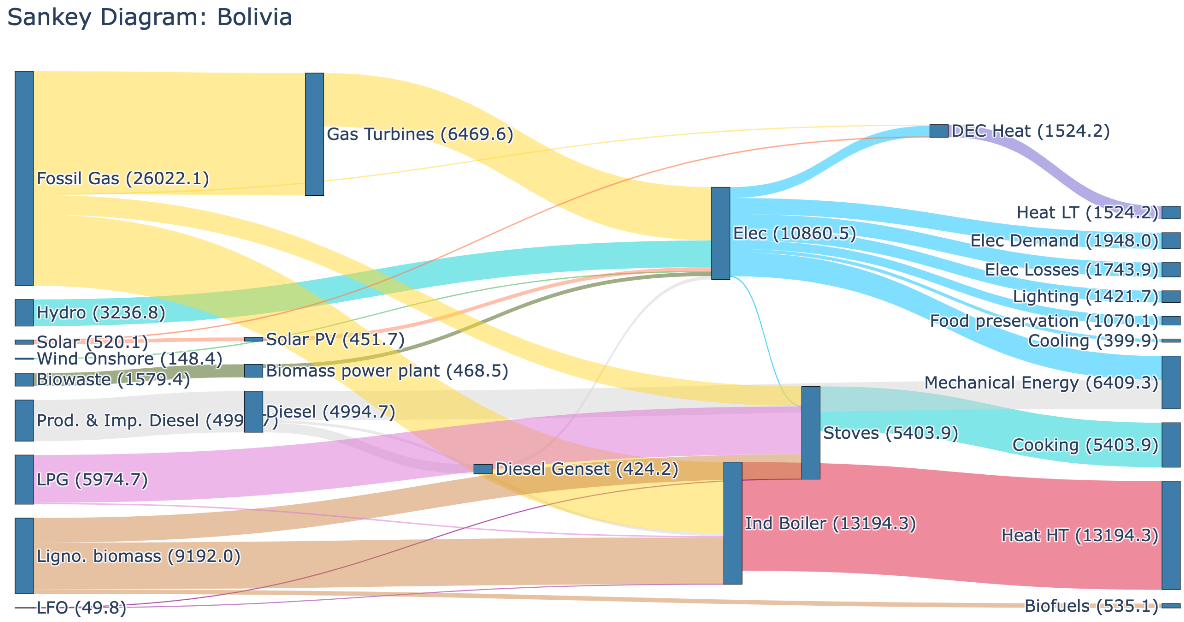

Figure B.10: Energy flow Sankey for all Regions, 2024 scenario.

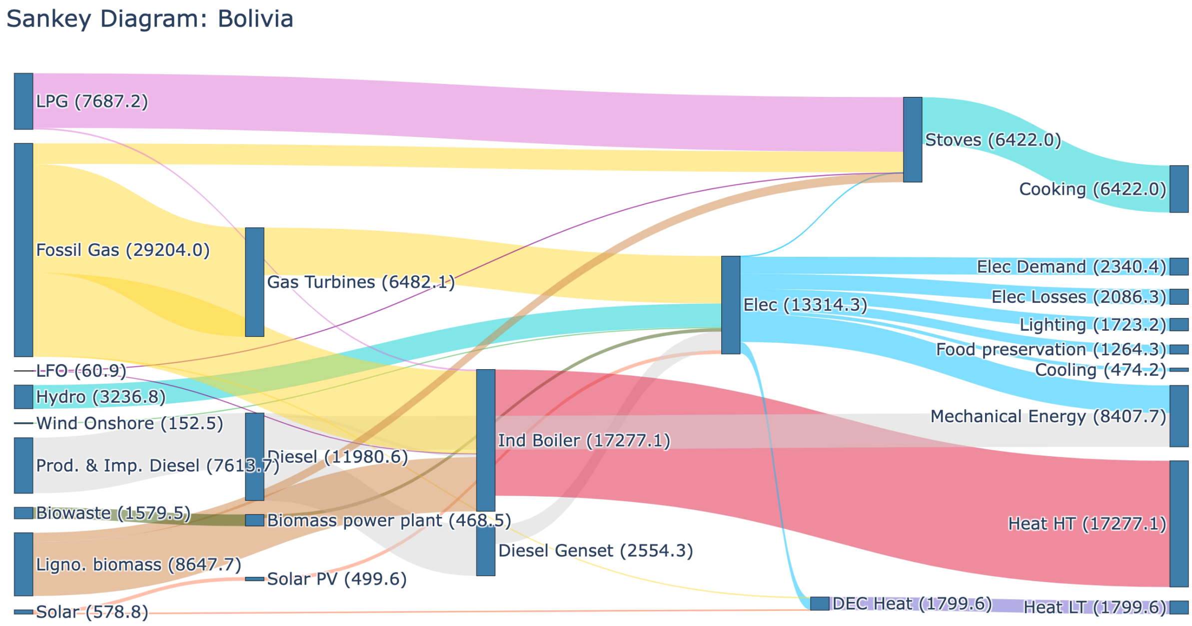

Figure B.11: Energy flow Sankey for all Regions, 2035 scenario.

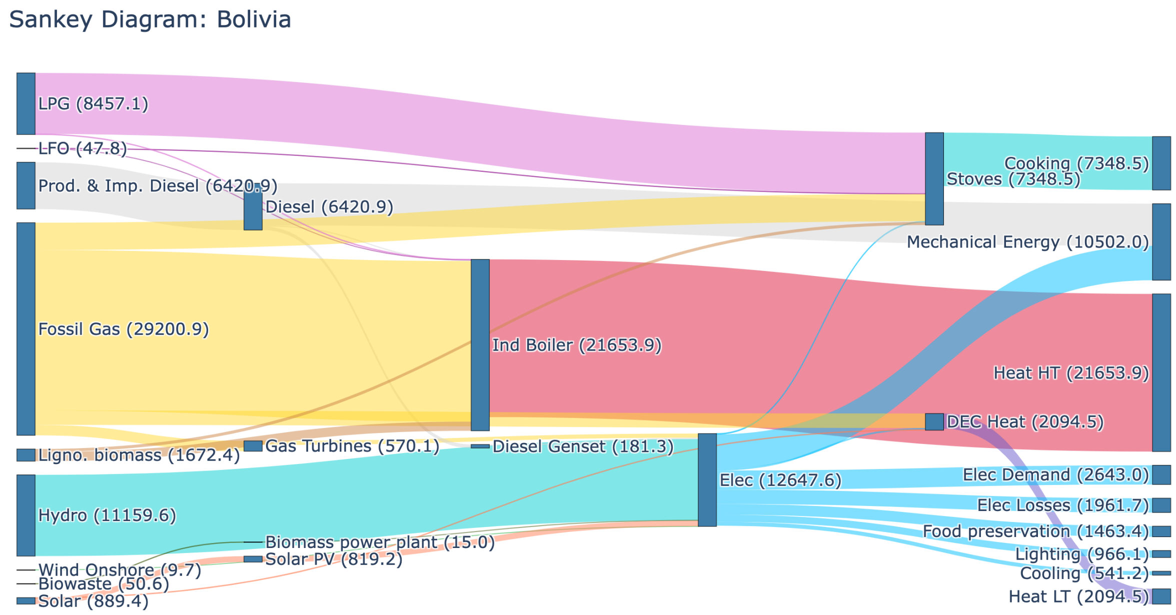

Figure B.12: Energy flow Sankey for all Regions, 2050 scenario.

Bibliography

[1] "WorldAtlas - Bolivia," Feb. 2021, section: WorldAtlas Geography. [Online]. Available: https://www.worldatlas.com/maps/bolivia

[2] Ministerio de Hidrocarburos y energía, "Plan Eléctrico Del Estado Plurinacional de Bolivia 2025." [Online]. Available: https://observatorioccdbolivia.wordpress.com/wp-content/uploads/2015/08/peebol2025.pdf

[3] M. de Planificación del Desarrollo, "Plan de Desarrollo Económico y Social 2021–2025," 2021. [Online]. Available: https://www.planificacion.gob.bo

[4] Vereinte Nationen, Ed., *The 2030 Agenda and the Sustainable Development Goals: an opportunity for Latin America and the Caribbean*, ser. United Nations publication. Santiago: United Nations, ECLAC, 2018.

[5] S. Pfenninger, A. Hawkes, and J. Keirstead, "Energy systems modeling for twenty-first century energy challenges," *Renewable and Sustainable Energy Reviews*, vol. 33, pp. 74–86, May 2014. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1364032114000872

[6] "Bolivia: Economía y demografía 2025 | Datosmacro.com." [Online]. Available: https://datosmacro.expansion.com/paises/bolivia

[7] "INE." [Online]. Available: https://censo.ine.gob.bo/

[8] Sergio Arnez Morales, "Desafíos del sector eléctrico boliviano." [Online]. Available: https://cbe.com.bo/noticia/desafios-del-sector-electrico-boliviano

[9] R. C. Delgado Alanes, "ESTUDIOS PARA LA CONEXIÓN DE INSTALACIONES DE GENERACIÓN Y TRANSMISIÓN AL SISTEMA ELÉCTRICO BOLIVIANO." [Online]. Available: https://biblus.us.es/bibing/proyectos/abreproy/70611/

[10] "Resumen Ejecutivo Balance Energético Nacional 2019-2023." [Online]. Available: https://www.mhe.gob.bo/wp-content/uploads/2024/07/Revista-Resumen-Ejecutivo-9-web.pdf

[11] F. Lombardi, S. Balderrama, S. Quoilin, and E. Colombo, "Generating high-resolution multi-energy load profiles for remote areas with an open-source stochastic model," *Energy*, vol. 177, pp. 433–444, Jun. 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360544219307303

[12] C. L. Sanchez Solis, P. Di Betta, N. Stevanato, S. L. Balderrama Subieta, E. Colombo, and S. Quoilin, "Electricity demand forecasting for rural communities

in developing countries: Calibrating a stochastic model for the Bolivian case." ULPGC, Las Palmas de Gran Canaria, Spain, Jun. 2023. [Online]. Available: https://www.proceedings.com/content/069/069564-0176open.pdf

[13] P. Thiran, A. Hernandez, G. Limpens, M. G. Prina, Hervé Jeanmart, and Francesco Contino, "Flexibility options in a multi-regional whole-energy system: the role of energy carriers in the Italian energy transition."

[14] Julien Jacquemin, Paolo Thiran, and Sylvain Quoilin, "Decarbonizing Western Europe: Extension of the Model 'EnergyScope MultiCell' for the Analysis of Renewable Fuel Potential."

[15] P. J. Zabalaga, G. Limpens, S. Meyer, P. Thiran, J. Villarroel-Schneider, and E. Cardozo, "Towards a sustainable Bolivian energy system in 2050: The pathway for decarbonization under high renewable potential." [Online]. Available: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5243304

[16] "GitHub EnergyScope Multicell Bolivia," Apr. 2025, original-date: 2024-10-25T22:16:31Z. [Online]. Available: https://github.com/CIE-UMSS/EnergyScope_Multicell_BO

[17] "Renewables.ninja." [Online]. Available: https://www.renewables.ninja/

[18] "Copernicus Browser." [Online]. Available: https://browser.dataspace.copernicus.eu

[19] C. Sanchez-Solis, S. Balderrama, G. Crevani, N. Stevanato, and S. Quoilin, "Bridging the energy gap: A Global South perspective on achieving universal access through energy sufficiency," *Energy for Sustainable Development*, vol. 88, p. 101793, Oct. 2025. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0973082625001437

[20] F. Lombardi, P.-F. Duc, M. A. Tahavori, C. Sanchez-Solis, S. Eckhoff, M. C. g. Hart, F. Sanvito, G. Ireland, S. Balderrama, J. Kraft, G. Dhungel, and S. Quoilin, "RAMP: stochastic simulation of user-driven energy demand time series," *Journal of Open Source Software*, vol. 9, no. 98, p. 6418, Jun. 2024. [Online]. Available: https://joss.theoj.org/papers/10.21105/joss.06418

[21] "GitHub - CIE-UMSS/RAMP_bolivia." [Online]. Available: https://github.com/CIE-UMSS/RAMP_Bolivia

[22] N. Stevanato, L. Rinaldi, S. Pistolese, S. L. Balderrama Subieta, S. Quoilin, and E. Colombo, "Modeling of a Village-Scale Multi-Energy System for the Integrated Supply of Electric and Thermal Energy," *Applied Sciences*, vol. 10, no. 21, p. 7445, Jan. 2020, number: 21 Publisher: Multidisciplinary Digital Publishing Institute. [Online]. Available: https://www.mdpi.com/2076-3417/10/21/7445

[23] P. Thiran, "Exploring options for a fossil-free European energy system : The role of renewable fuels," Ph.D. dissertation, UCL - Université Catholique de Louvain, 2024. [Online]. Available: https://dial.uclouvain.be/pr/boreal/object/boreal:293132

[24] "List Of Restaurants in Bolivia." [Online]. Available: https://rentechdigital.com/smartscraper/business-report-details/list-of-restaurants-in-bolivia?utm_source=chatgpt.com

[25] Pablo Jimenez Zabalaga, Carlos A. A. Fernandez Vazquez, Rober Mamani, Evelyn Cardozo, and Hervé Jeanmart, "Multi-Scale Wind-Solar Energy Assessment with Infraestructure Cost Integration: A Case Study of Bolivia."

[26] "CIE-UMSS/atlite_bo," May 2025, original-date: 2025-05-12T07:56:35Z. [Online]. Available: https://github.com/CIE-UMSS/atlite_BO

[27] W. Fuentes Crispin, "ANÁLISIS DE COSTOS PARA LA IMPLEMENTACIÓN DE SISTEMAS FOTOVOLTAICOS AISLADOS EN COMUNIDADES REMOTAS DEL TERRITORIO INDÍGENA ORIGINARIO CAMPESINO DE RAQAYPAMPA," Ph.D. dissertation, Universidad del Valle.

[28] Munir Husein, Hyung-Ju Kim, and Il-Yop Chung, "The Impact of Policy and Technology Parameters on the Economics of Microgrids for Rural Electrification: A Case Study of Remote Communities in Bolivia." [Online]. Available: https://www.mdpi.com/1996-1073/13/4/877

[29] S. L. Balderrama Subieta, "Optimal design and deployment of isolated energy systems: The Bolivian pathway to 100% rural electrification," Doctoral Thesis, University of Liège, Apr. 2022.

[30] EU, "D2.8 / D2.9_standardized model and cost/benefit assessment for right size engines and hybrid configurations." [Online]. Available: https://www.prominent-iwt.eu/wp-content/uploads/2018/07/18_03_13_PROMINENT_D2.8_D2.9_Standardized_model_and-cost_benefit_assessment_for_right-size_engines_and_hybrid_configurations.pdf

[31] Tomás Undurraga Henríquez, "IMPLEMENTACIÓN Y EVALUACIÓN DE UN SISTEMA HÍBRIDO (SOLAR-DIÉSEL)," Ph.D. dissertation, Universitat Politècnica de Catalunya. [Online]. Available: https://upcommons.upc.edu/bitstream/handle/2117/173251/TFG_UNDURRAGA_TOMAS.pdf?sequence=1&isAllowed=y#:~:text=Es%20conclou%20la%20import%C3%A0ncia%20del,Finalment%20es%20realitza%20una%20an%C3%A0lisi

[32] "World Development Indicators | DataBank." [Online]. Available: https://databank.worldbank.org/reports.aspx?source=2&country=BOL

[33] T. Moss, M. Bazilian, M. Blimpo, L. Culver, J. Kincer, M. Mahadavan, V. Modi, B. Muhwezi, R. Mutiso, V. Sivaram, J. Taneja, M. Thurber, J. Urpelainen, J. H. Sais, and M. Webber, "The Modern Energy Minimum:."