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Electricity demand forecasting for rural communities in developing countries: Calibrating a stochastic model for the Bolivian case

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Abstract:

The world crusade to close the electrification gap is coming to an end in most regions of the world. In recent years the research in the area has concentrated on the development of planning methods to minimise the cost of implementation. Although successful, the lack of focus on the complex dynamics that govern electricity demand lead to over/under-sizing of technical solutions resulting in waste of resources and missed developing opportunities. In this sense, this paper aims to propose an electricity demand model for rural communities in Bolivia, based on an open-source bottom-up stochastic tool for load profile computation. The "energy sufficiency" concept is used to ensure that people's basic needs for energy are met in all the analysed cases. Information from various sources, such as on-site surveys, databases and national reports were used to characterise the main geographical areas in Bolivia and the relative specific categories of users. Specific load curves generated with the model were used as inputs in a micro-grid sizing tool and the results were compared with an approach using a demand analysis in less detail. Main results show that the model obtained is capable of generating stochastic demand curves for single or multiple rural communities according to contextual particularities. Notably, the geographic location and the socio-economic characteristics have a significant impact in the peak loads and the total demand. Considering small industries as an income generating activity can increase in the peak load by about 45%, consequently, there is an economic impact when investing in the solution.

Keywords:

Rural electrification, developing countries, energy sufficiency, energy demand

1. Introduction

The global effort to close the electrification gap has made significant progress in recent years moved by the Sustainable Development Goal 7 [1]. However, much of the research in this area has focused on minimizing the cost of implementation, often at the expense of considering the complex dynamics that govern electricity demand in rural communities [2]. This narrow focus has led to the implementation of technical solutions that are either oversized or undersized, leading to resource wastage and missed opportunities for development. [3, 4]. Therefore, it is crucial to develop planning methods that consider the specific contextual factors influencing electricity demand in rural communities [5]. This approach ensures that technical solutions are adequately sized and effectively meet the basic energy needs of the population [6]. In order to achieve this, the selection of the optimal electricity supply strategy and the capacity of the local generation and storage system heavily rely on the anticipated electricity usage. This demand is determined by both the shape and height of the hourly load curve, as well as the overall energy consumption, as evidenced in [7].

According to the literature, there is a wide range of energy modelling tools with different scopes and capabilities to support energy planning at different scales. However, it is clear that there are still challenges related to the demand side, that need to be addressed [8]. Energy System models have demonstrated limited representativity of societal transformations such as behaviour of actors, transformation dynamics on time and heterogeneity across and within societies, that could potentially have impacts in the demand side [9, 10]. Regarding to demand estimation tools, [11] concludes that deterministic models for energy demand estimation are simpler to comprehend and use, but the results they generate are inflexible and have limited information. Conversely, stochastic methods require more resources and complex mathematical models but offer a more precise understanding of demand scenarios. In [12], the authors incorporated high-resolution demand estimation to an energy planning process, however, there is still room to improve the level of detail in the estimation in sectors such as productive activities.

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Although there is no universally recognized definition for energy access, the literature frequently uses the term to describe a scenario in which individuals have access to modern energy sources and affordable end-use technologies [13, 14]. It is worth noting that while facilitating access to improved energy carriers is essential, it alone is inadequate for achieving broad-based poverty reduction and promoting socioeconomic development [14]. In this regard, recent studies have examined the impact of incorporating energy sufficiency scenarios in the context of electricity demand in Bolivia to estimate the amount of energy rural communities might need [15]. The current research aims to contribute to this effort by calibrating a bottom-up stochastic tool that can effectively capture the distinctive characteristics of the electricity demand in a developing country context.

2. Methodology

This section outlines the methodology employed to achieve the proposed objective. The approach encompasses four primary stages, as illustrated in Figure 1. In the first stage, an analysis was conducted on the database containing historical electricity consumption per household situated in rural areas where the rural communities already possess access to electricity. Through this analysis, significant variables that affect residential electricity consumption and typical monthly aggregate consumption ranges for each region were identified.

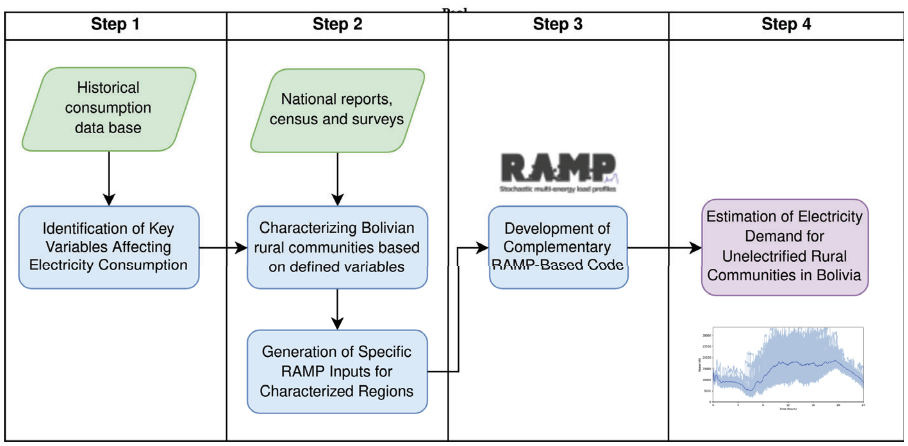

Figure 1: Flowchart of the four-step methodology

The second stage involved developing tailored inputs for the RAMP model for the region under study. This was achieved by considering the different sectors of energy consumers in the rural communities. The inputs for the RAMP model were created using the data obtained from in site surveys from previous studies, which were then cross-checked and replicated closely with the monthly aggregate consumption data acquired in the preceding stage. National reports and standards were employed to construct the RAMP inputs for the remaining sectors.

The third stage focuses on the development of a tool for village load formulation based on RAMP model, to utilize the tailored inputs created in the previous stage to generate stochastic load curves that are appropriate for specific scenarios. The model is designed to incorporate the most critical variables identified in the first stage. In the final stage of the study, the model is employed to generate load curves for rural communities in developing countries based on different established scenarios. These scenarios involve communities with different characteristics, thereby providing insights into how demand varies across diverse contexts.

2.1. A bottom-up stochastic tool for estimation of energy demand: RAMP

The RAMP tool is a stochastic model that operates from the bottom-up and is capable of generating load curves based on user behavior. It is a valuable tool for exploring the demand of remote communities and as an initial step towards sizing appropriate energy systems. The tool is built upon three layers: users, user types, and appliances. The top layer involves defining various User types (such as households, commercial activities, public offices, hospitals, etc.) based on the modeller's discretion. The level of detail for each User type can vary depending on the available information, for example, households can be divided into income classes or building types for greater precision. The second layer involves determining the number of individual Users associated with each User type, while the third layer focuses on the Appliances owned by each User. This three-layer structure enables independent modeling of the behavior of each Appliance and the creation of a unique load profile for each individual User within a given User type. Aggregating all independent User profiles generates a total load profile that is different for each model run, replicating the unpredictability of users' behavior and producing a range of daily profiles. Further information about the model can be found [16]. In order to approach the reality of a community or region as accurately as possible, it is essential to conduct a detailed characterization of its users. This is particularly important when studying the electricity demand of communities that have yet to gain access to electricity, and it represents a significant challenge.

3. Case of study

3.1. The Bolivian Context

Bolivia, a South American nation, is yet to achieve complete electrification coverage across its entire territory. However, universal access to electricity has been set as a national target to be achieved by 2025. As of 2018, the country had registered a national electricity coverage of 93 %, with 99% of urban areas and 80% of rural areas covered [17]. According to a previous study, rural communities with fewer than 50 households were mainly low-income and might not generate enough demand to make micro-grids economically feasible. Furthermore, the dispersed nature of some of these communities complicates the installation of a local grid [18].

3.2. Main regions of geographic importance

The rural communities in Bolivia are distributed throughout the country's three geographic regions: lowlands, valleys, and highlands. The National Agricultural Compendium [19] describes the characteristics of these regions. The lowlands span over an area of 670,000 km2 and exhibit a diverse mixture of land uses, tenure systems, and actors ranging from indigenous peoples to small-scale farmers and agro-businesses. The valleys are situated between 1800 and 3000 meters above the sea level and are known for their narrow valleys, rough terrain, and moderate climate. The highlands are defined as regions situated at an altitude exceeding 3000 meters above sea level, primarily located in the western part of the country, and inhabited by numerous remote indigenous communities. Agriculture is a significant activity in all three regions, with temperature, precipitation, and altitude serving as fundamental factors in determining the productive potential and production systems. It is noteworthy that cultural disparities exist among these regions, which could potentially impact individuals' attitudes and practices towards electricity consumption.

3.3. Rural community structure

The structure of the rural communities in Bolivia has been previously defined in [15], which comprises a residential consumption sector (RS), a community services sector (CS) and an income generating activities sector (IGA).

The Electricity Authority's 2020 Statistical Yearbook [20] indicates that the residential sector represents the largest portion of national electricity demand (both in the National Interconnected System and in the Isolated Systems), accounting for 43.56% of the total. This is followed by the industrial sector at 22.2%, the general category at 18.8%, mining at 6.4%, and public lighting and other sectors at 9%. The 2016 National Demographic and Health Survey in Bolivia [21] reveals the prevalence of various electrical appliances in households across different regions of the country that are notably different. Community services aim to provide education, health services, and clean water to the population, and common infrastructure for this purpose includes hospitals, schools, drinking water supply systems, and sports facilities.

Income-generating activities (IGA) in Bolivian rural areas are primarily agricultural and livestock-based, with 78% of the employed population working in this sector [22]. However, non-agricultural activities also contribute to the income of rural households, with 22% of the population engaged in manufacturing, sales and repairs, and construction. Livestock activities are important sources for improving the income of rural households, with more than 12% of rural household income coming from livestock activity and derived products. Agricultural production has low productivity and generally faces low prices in the market, but self-consumption of agricultural products provides food security for rural households [23, 24]. Different types of irrigation are used for agricultural activities, and the transformation of agricultural products is an important form of economic diversification in rural communities. Non-agricultural IGA's vary by region, reflecting the characteristics of local idiosyncrasy. Energy needs for IGA should not be neglected, as access to electricity can impact rural economies, with the transformation processes of agricultural products representing an opportunity for growth and diversification.

4. Results and discussion

The results obtained from the characterization of rural communities and their energy consumer groups, which were incorporated into the design of the tool, are presented in this section. Subsequently, the analysis of the demand profiles generated with the model is presented.

4.1. Generation of tailored inputs for RAMP

The findings of the initial phase of the investigation reveal the impact of certain variables on electric power consumption in rural communities that are connected to the main grid. The analysis of the database was

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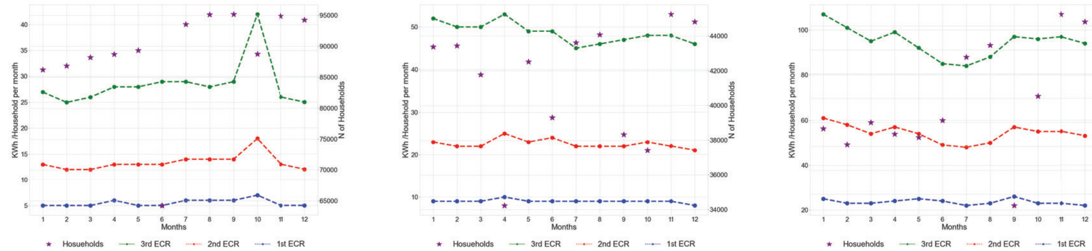

(a) Highlands (b) Valleys (c) Lowlands

Figure 2: Quartiles of electricity consumption of electrified households in rural areas.

initially developed by filtering the data of consumers in rural areas, classified in the three defined regions. A correlation analysis was performed using variables such as percentage of poverty, geographic location, proximity to roads, among others, corresponding to the municipality to which these residential consumers belong. The results of this analysis show that the variables of impact on electricity consumption at a residential level are: the geographic location or altitude and the household income.

To characterize and generate taylored inputs for RAMP, a range of information sources were utilized, including site surveys, national reports, and databases. Site surveys conducted specifically for the purpose of generating RAMP inputs for previous studies [25–27] were used as a point of reference, conducted in rural communities such as El Espino, La Brecha, El Sena, and Raqaypampa, located in distinct geographical regions across the country. Additionally, the 2012 Census national database [28] was employed, with demographic data projected through 2025. To determine the variables with the most significant impact on energy consumption at the national level, the electricity consumption database from [29] was utilized to validate variables that influence electricity consumption.

4.1.1. Residential sector

The 2016 National Demographic and Health Survey in Bolivia [21] reveals the prevalence of various electrical appliances in households across different regions of the country. Radios, televisions, and cellphones are the most commonly used appliances in both low and high poverty municipalities, which are predominantly rural communities. Refrigerators are more commonly used in low poverty regions of the lowlands compared to the highlands, where temperatures are lower. Radios are more frequently used than TVs in high poverty regions. Access to modern appliances is limited in high poverty regions [30]. Although different types of family composition have been recorded among the communities, the average number of persons per household in rural areas of Bolivia is 3.1, according to the 2016-2017 Household Survey [31].

To gain an overview of residential electrical consumption, it was possible to perform an statistical of the monthly electricity consumption ranges that represent general behavior over the course of a year, using the mentioned data base from [29]. This was achieved by computing the median of all percentile threshold values for each month. By identifying the most representative consumption ranges in this way, as showed in figure 2, it is possible to use them to characterize the electrical consumption patterns of low, middle, and high-income households in all three regions under consideration.

Figure 2 highlights the significant regional disparities in electricity consumption. The harsh living conditions in the highlands result in the lowest consumption rates. Conversely, the valleys have much higher electricity usage than the highlands, typically consuming twice as much across all consumption ranges. However, it is in the lowlands that the most substantial impact on overall electricity consumption is present, with values almost twice as high as those of the valleys. The reason behind this effect relies on tend to use appliances to improve the comfort due to high temperatures. Moreover, the use and energy consumption of refrigerators are also influenced by these temperatures, as demonstrated in [32, 33].

The findings of the study highlight the importance of taking into account the unique characteristics of different regions when modeling electricity usage in rural communities. By doing so, it becomes possible to more accurately capture the diverse needs and behaviors of households across the country. However, it was found that the difference in consumption between households was mainly driven by one appliance, namely refrigerators. Therefore, the study focused on only two categories of residential users, high-consumption and low-consumption, based on their overall electricity usage. The RAMP appliance configuration used in the study was designed to adequately represent these behaviors, which were consistent with the results of on-site surveys. This approach can help researchers and policymakers make informed decisions about energy planning and management in rural communities, taking into account the specific characteristics and needs of different regions.

4.1.2. Community Services Sector

To deliver community services, appropriate infrastructures are needed including hospitals, schools, drinking water supply systems, sport facilities, public lighting and churches. government-mandated norms and standards for the community sector are uniform across the country, and as a result, altitude don't have any effect on the composition and characteristics of the energy users of this sector. This means that the list of appliances and the usage patterns associated with each service will remain unchanged. The only variation across different regions considered is in the behaviours of thermal appliances, which is determined by the average temperature of the targeted area.

Therefore, the selection of various types of facilities took place using specific criteria for different services. The criteria assumed for this methodology are described in the following sections for each type of facility considered and summarized in Table 1a.

Table 1: Criteria for the allocation of a) community services infrastructure and b) IGAs in rural communities according the population size of the communities

(a)

Infrastructure	Criteria
1 Health post	if 500-1000 inhab.
1 Health center	if more than 1000 inhab.
1 Public lighting post	per every 10 HH
1 Sport field	if more than 500 inhab.
1 Church	if more than 500 inhab.
1 Water supply system	per every 100 HH
1 School A	if less than 100 inhab.
1 School B	if 100-500 inhab.
1 School C	if more than 500 inhab.

(b)

Activity	HL	VA	LL
1 Irrigation system	30HH	22HH	18HH
1 Transformation activity	200HH	200HH	200HH
1 Grocery store	25HH	25HH	30HH
1 Restaurant	30HH	30HH	30HH
1 Workshop	80HH	70HH	60HH
1 Entertainment center	100HH	80HH	60HH

4.1.2.1 Health facilities

For this infrastructure, the "National Norm for the Characterization of Primary Health Care Facilities" [34] sets guidelines and standards for its availability in rural areas, including infrastructure and equipment requirements. For communities with a population between 500 and 1000, a "health post" is mandated, while for those with between 1000 and 10,000 inhabitants, a "health centre" with the capacity for hospitalization is required. If a community has fewer than 500 residents, it must be within a two-hour driving distance from both low and high-capacity healthcare facilities. The equipment ownership data per facility type was collected from the norm as well.

4.1.2.2 Educational facilities

With regards to education, three types of schools have been identified as the most common in rural areas, based on community size. Type A schools are small multi-level establishments located in the smallest and most remote communities with a population of less than 100 people. Type B schools have a larger number of classrooms and offer a range of instruction from primary to secondary education, with double-shift operation for communities with a population between 100 and 500. Type C schools are well-equipped educational institutions that can accommodate a greater number of students, typically in larger villages near cities or major roads when the population exceeds 500 [34]. Access to educational facilities remains a significant challenge for those living in rural areas. For example, education coverage still stands at 73-83% in the lowlands, indicating that significant improvements are still possible despite recent progress [34].

4.1.2.3 Drinking water supply systems

The type and characteristics of drinking water systems are influenced by the availability of water resources and the terrain in which the community is located. However, a standard water supply system has been chosen for each type of community in this study [35], as the modeling of these systems is not the primary focus. Future research could aim on doing a more in-depth characterization of water supply systems, as they are crucial for the health and well-being of rural communities, as emphasized by the Sustainable Development Goal 6 (SDG 6).

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4.1.2.4 *Public lighting and other community services*

The presence of streetlights in rural communities is guided by the standards set forth in a document published by the energy ministry [35], which provides guidelines for the implementation of energy access projects. Accordingly, the guideline states that a streetlight must be installed for every 10 households in a community.

In recent years, the availability of sports facilities in rural communities has increased due to government health policies, as the Supreme Decree No. 1868 of the 2014 testifies [36]. As a result, in this work is considered that communities with a certain number of inhabitants will have this kind of community services.

4.1.3. Income Generating Activities

Income generating activities are defined as responsible for income increase or productivity growth. Neglecting the energy needs of IGA increases the risk of energy marginalization in rural communities, leading to greater energy inequality and a significant underestimation of the communities' total energy needs [37]. This sector is divided into agricultural and non-agricultural activities. Non-agricultural activities include grocery stores, restaurants, workshops, and entertainment businesses , while agricultural activities encompass irrigation systems and the processing of agricultural products.

As already done for the other two sectors, it is fundamental to explore how the three drivers influence the modelling of IGAs. Naturally, agricultural activities are substantially influenced by altitude as it serves as a crucial determinant for the viable sustenance of various plant and animal species [38]. Consequently, irrigation and transformation activities are affected.

Non-agricultural IGAs are reflect the local idiosyncrasies of each region. For instance, certain areas in the lowlands, like the Beni region, have a higher concentration of recreational and food businesses [39]. Taking into account these regional variations is crucial for modelling, but it can also be a complex task due to the limited availability of this type of data. For this reason, the empirical formulas presented in Table 1b are an estimation that aims at capturing the frequency of appearance of these businesses, based on [39], [40], [41].

The level of UBN in a community determines the composition of its energy sectors. As already mentioned, based on a specified level of poverty, the selection of IGA energy users follows the rules outlined in 2. Consequently, each community IGA user will be included in the community structure only if a certain UBN threshold is met.

In the other hand, the number of IGA users is influenced by specific regional criteria, but the overall number is also considered proportional to the total population, which is calculated using an empirical formula. For example, in the highlands, there is one grocery store for every 25 households, while in the lowlands, there is one grocery store for every 30 households. The criteria assumed for this methodology are explained in the following sections for each type of IGA considered and summarized in Table 1b.

4.1.4. Irrigation systems

In rural areas, there are various types of irrigation systems, some of which require electricity while others do not. Most of the irrigation relies on flood-gravity techniques, which cover around 97% of the irrigated land. However, there has been an increasing adoption of modern irrigation methods such as sprinkler or drip irrigation, which account for the remaining portion. Based on the "Irrigation Development National Plan" [42], the majority of requested irrigation projects in rural areas are of micro or small typologies. To simplify the analysis, it is assumed that rural villages are more likely to have small or micro systems that include an electric pump and a drip irrigation system. It is also assumed that each system can cover up to ten acres of cultivated land.

The total number of irrigation systems is determined by a function of the population, taking into account the number of households and the region they belong to. This correlation is derived from a simple analysis of irrigation system databases, specifically by studying the distribution of irrigation systems across Bolivia [43]. The variation in the number of irrigation systems aims to reflect differences in climatic conditions and rainfall volume, as well as the significance of the agribusiness industry in the region. However, as the primary focus of this study is not on modelling these systems, and due to the potential complexity of such task, it is suggested that future research could explore deeper into characterizing these systems.

4.1.5. Transformation activities

Agricultural product transformation can boost economic growth, diversifying the source of income while increasing the electricity consumption due to the need of processing equipment and machinery [44]. Among governmental and non-governmental support programs, the provision of equipment is often included to support the processing. However even after access to electricity, the thriving of processing products remains challenging.

In this context, one processing activity has been selected for each region and will only be introduced once the energy sufficiency status is achieved. Extensive analysis, based on [38], was conducted to select relevant processing activities for each region and for the national context. Therefore, Quinoa processing was selected for the highlands, cereal processing for the lowlands, and a small-scale dairy industry for the valleys.

The seasonal behaviour of quinoa and cereals must be taken into account for these processing activities, and therefore these activities are only modelled during the harvest period, which typically spans from July to October [38]. Additionally, to determine the number of processing units, it was decided to introduce one unit for every 200 households, based on [44], with the exception of the milk dairy industry, which has a fixed assumed number of one unit. The details of all users defined and characterized for each zone, the appliances associated with each of them and their use characteristics can be found in the repository `https://github.com/CIE-UMSS/RAMP_Bolivia.git`

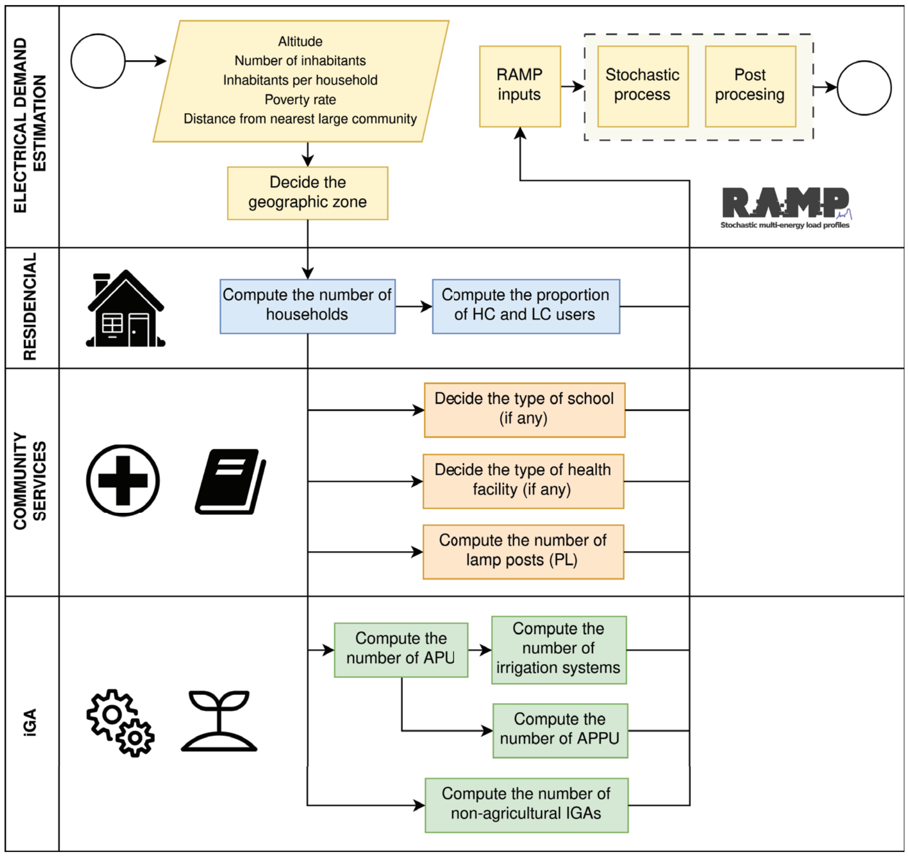

Figure 3: RAMP inputs creation per community

4.2. Estimation of Electricity Demand for Unelectrified Rural Communities in Bolivia

The model, which is based on RAMP, enables the generation of load curves for remote communities situated within Bolivian territory. The inputs for the model include community size, altitude (which determines the region in which the community is located), the proportion of high and low consumption (defined by the UBN), the average number of people of a family. A summary of how the complementary model works to calculate energy demand based on the mentioned data is shown in figure 3

The electricity demand for a year was simulated for four different scenarios in each region. The characteristics provided by the complementary model for these scenarios, in the form of RAMP inputs, can be seen in the Table 2, which represent four different states that theoretically improve living conditions since the percentage of poverty decreases and the availability of community services is greater. Likewise, economic diversification improves. The four archetypes where simulated for a community of 500 inhabitants in each one of the three important regions.

Figure 4 illustrates the computed annual electricity demand for each scenario. The aggregate demand and the participation of each sector within it can be observed. Notably, annual aggregate demand is higher in the lowlands and decreases at lower altitudes. This is partly due to the behavior of residential demand, described in section 4.1.1., and to the predominance of this sector's demand in overall demand. On the other hand,

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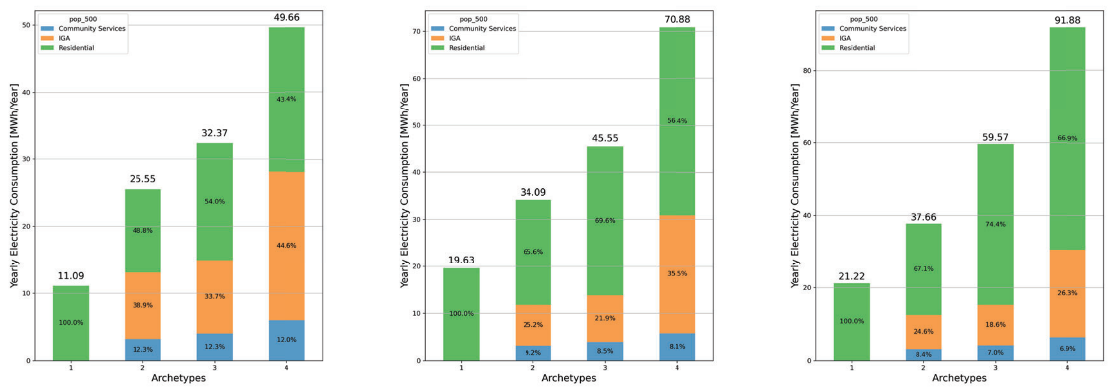
Table 2: Four scenarios considered for each community size.

N°	Poverty (%)	Community Services	Agricultural IGA's	Non-agricultural IGA's
1	96	No community Services	No irrigation or transformation	No commerce
2	90	Public lighting + water supply system	No irrigation or transformation	Grocery stores + restaurants
3	70	Public lighting + water supply system + school	Irrigation	Grocery stores + restaurants
4	53	Public lighting + water supply system + school + hospital + other community services	Irrigation + transformation	Grocery stores + restaurants + workshops + entertainment business



(a) Highlands

(b) Valleys

(c) Lowlands

Figure 4: Simulated yearly demand for rural communities of 500 inhabitants in the highlands, valleys and lowlands of Bolivia

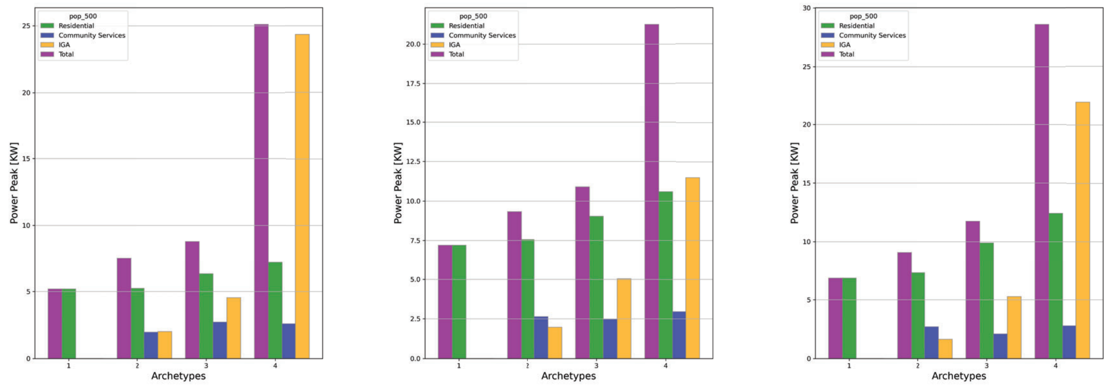
it can be observed that the share of IGAs in the aggregate consumption of the highlands reaches a higher share because the production and transformation processes of typical products of these regions tend to be more costly in terms of energy consumption. The demand corresponding to the community services sector experiences a slight increase from region to region due to the thermal appliances owned by users within this group.

Analyzing the peak loads showed in Figure 5, it can be observed that in the lowlands, the peak load reaches about 28KW as opposed to the lowlands, where it reaches around 25KW. However, the main contribution in both cases is made by the activities related to the transformation of products. Again, in the case of the IGAs in the highlands, the contribution to the peak is higher due to the complexity of the equipment required in the processes selected for the region.

Figure 6 shows an example of a load curve generated for a community in the lowlands using RAMP. It is possible to appreciate the stochasticity with which the 365 daily profiles (one year) are generated, from which an average daily load curve is computed. The peak load range is observed between 12 noon and 6 p.m. in this case.

5. Conclusion

The estimation of electricity demand in remote communities is a crucial yet challenging task for energy planning. This study aimed to calibrate a bottom-up stochastic tool to generate load curves for rural communities in Bolivia. Although previous research has recognized the need to improve demand analysis processes, they



(a) Highlands (b) Valleys (c) Lowlands

Figure 5: Simulated peak loads for rural communities of 500 inhabitants in the highlands, valleys and lowlands of Bolivia

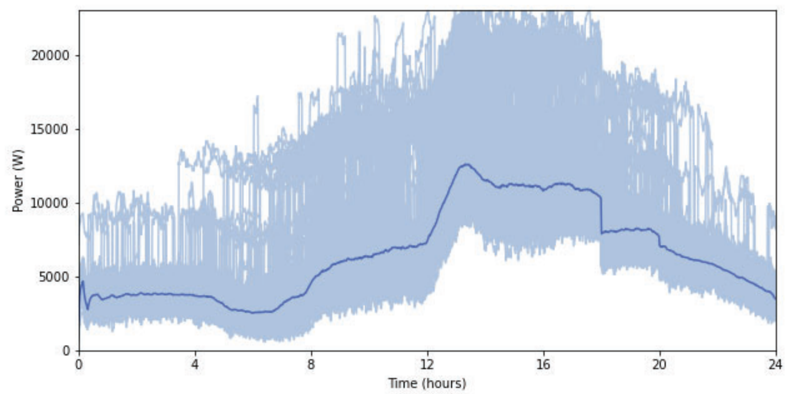


Figure 6: Average load curve computed with RAMP for a community with a population of 500 people in the LL, with scenario 4 characteristics (according Table 2)

have rarely considered energy use related to income-generating activities. Additionally, demand phenomena are strongly linked to contextual factors, requiring careful calibration and adjustment processes. However, the RAMP tool proved to be a powerful tool in capturing specific features of the zones under study to formulate adequate load curves. The biggest challenge remains obtaining accurate calibration information.

Exploring energy demand across consumer sectors and rural communities can provide useful insights for energy planning towards universal access. The proposed model enables the calculation of rural communities' demand using critical characteristics such as size, poverty rate and altitude. The study successfully simulated demand for rural communities from various regions of Bolivia, capturing the particular characteristics that highlight the main differences between the regions in terms of peak loads and aggregated demand. This study emphasized the high impact of geographical location on energy use and the electricity needs for productive uses, which depend on regional potential. Future work includes improving the model for serial computation of the demands of multiple rural communities.

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system models for energy planning in Bolivia".

Nomenclature

LL Lowlands,

VA Valleys,

HL Highlands,

IGA Income Generating Activities,

PL Public Lighting,

RS Residential sector,

RS Community Services,

UBN Unsatisfied Basic Needs

HH Households,

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