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

Claudia Sanchez[a,c], Pietro Di Betta[b], Nicolo Stevanato[b], Sergio Balderrama[c], Emanuela Colombo[b] and Sylvain Quoilin[a]

[a] Universite de Liege, Liege, Belgium, clsanchez@uliege.be,CA
[b] Politecnico di Milano, Milano, Italy,
[c] Universidad Mayor de San Simon, Cochabamba, Bolivia,

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. The applicability of the results is of paramount importance in energy planning processes at various levels.

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. 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 [1]. This narrow focus has resulted in technical solutions that are either over or under-sized, resulting in wasted resources and missed opportunities for development [2, 3]. Therefore, it is important to develop planning methods that take into account the specific contextual factors that influence electricity demand in rural communities, in order to ensure that technical solutions are appropriately sized and that the basic energy needs of the population are met [4].The selection of the optimal electricity supply strategy and the capacity of the local generation and storage system heavily rely on the anticipated local electricity usage. This demand is determined by both the shape and height of the hourly load curve, as well as the overall energy consumption.

However, estimating the electricity demand is a challenging task, particularly in communities without prior access to electricity, as it involves modeling human behavior associated with energy consumption and anticipating its evolution over time, taking into account the complex social transformations that may occur after electricity access [5].

Over time, tools have been developed to support energy planning at different scales. According to the literature, there is a wide range of energy modelling tools with different scopes and capabilities. However, it is clear that there are still challenges related to spatio-temporal variability and openness as well as the demand side that need to be addressed in the development of future tools [6]. Energy System models have demonstrated limited representations of societal transformations such as behaviour of actors, transformation dynamics on time and heterogeneity across and within societies [7, 8]. In this sense, this work focuses on addressing the issue of electric demand analysis, where, according to the literature, there is room for improvement. According to [9] ,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, complex mathematical models, and interpretations but offer a more precise understanding of demand scenarios. For this reason, this study focuses on the utilization of a stochastic tool.

Research has been conducted to enhance and develop tools aimed at facilitating energy planning. However, there remains a gap in the formulation of tailored load curves for remote regions that not only consider residential demand, but also other demands [10].

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 [11, 12]. It is worth noting, however, that while facilitating access to improved energy carriers is essential, it alone is inadequate for achieving broad-based poverty reduction and promoting socioeconomic development [12]. In this regard, recent studies have examined the impact of incorporating energy sufficiency scenarios in the context of electricity demand in Bolivia. The findings demonstrate a significant effect, which could have far-reaching implications at the investment and energy policy levels [13]

Against this backdrop, the objective of this study is to calibrate a stochastic tool-based electricity demand model for Bolivia, which accurately captures the unique features of the Bolivian context.

2. Methods

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

The study's second stage involved developing tailored inputs for the Rural Access to Modern Energy (RAMP) model for the three designated geographical zones of interest. This was achieved by considering the composition of the rural communities, as defined in the first stage, which comprises three sectors: residential, community services, and Income Generating Activities (IGAs). The inputs for the RAMP model were created using the data obtained from the aforementioned surveys, 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 of this study involves the development of an additional code that can use the customized inputs created in the previous stage to generate appropriate load curves. This code utilizes the most significant variables identified in the first stage. The final stage of the study involves the testing of the model by generating load curves for rural communities in Bolivia with varying characteristics located in different regions of the country. The study also calculates the total demand of all rural communities without access to electricity by utilizing data from the 2012 Census to obtain the required variables as inputs corresponding to each community. Fig X illustrates the flowchart of the study.

Flowchart of the three-step methodology-eps-converted-to.pdf

Figure 1: Flowchart of the three-step methodology

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 operates on three layers: users, user types, and appliances, of which, detailed information is required as input. Further information about the model can be found [14]. Therefore, in order to approach the reality of a community or region under study 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.

In this specific instance, RAMP was utilized to generate electricity demands in remote areas, taking into account the unique features of the country under study. In order to accomplish this, RAMP inputs were derived from the characterization of geographical regions across the country. This was achieved by utilizing various sources of information, including on-site surveys, national reports, and databases.

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 [15]. According to a previous study, 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 [16].

3.1.1. Main regions of geographic importance

The aforementioned communities are distributed throughout the national territory, which encompasses three distinct geographic regions: highlands, valleys and lowlands. The National Agricultural Compendium [17] describes the characteristics of these regions and their productive potential. The Bolivian lowlands (LL) refer to the land situated in Bolivia below 500 meters above sea level, spanning over an area of 670,000 km2, bordered by the Andes in the West and neighboring countries in other directions. This region exhibits a diverse mixture of land uses, tenure systems, and actors ranging from indigenous peoples and communities to agro-businesses, traditional cattle ranchers, and small-scale farmers engaged in commercial agriculture. The valleys are situated between 1800 and 3000 m.a.s.l between the Andean mountain range and the lowlands.. It is known for its narrow valleys, rough terrain, and moderate climate. The region is home to a diverse range of ecosystems, such as cloud forests, dry forests, and high-altitude grasslands. The valleys are inhabited by a mixture of indigenous communities, small-scale farmers, and urban areas, including Bolivia's largest city, Santa Cruz. Agriculture is a significant industry in the valleys, with crops such as coffee, coca, and citrus fruits being cultivated. The region is also rich in minerals, with mining playing a vital role in the local economy. The valleys have been the subject of numerous studies that have addressed various concerns, including land use, water resources, and rural development. The highlands of Bolivia 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. Due to lower temperatures compared to the lowlands, humidity levels in this region are reduced, with rainfall generally being stationary and its distribution decreasing from northeast to southwest. A diverse range of agricultural crops are cultivated in various ecosystems across the lowlands, valleys and highlands, with temperature, precipitation, and altitude serving as fundamental factors in determining the productive potential and production systems.

3.2. Rural community structure

The structure of the rural communities in Bolivia has been defined in [13], . The 2016 National Demographic and Health Survey in Bolivia [18] 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 [19]. The average number of persons per household in rural areas of Bolivia is 3.1, according to the 2016-2017 Household Survey [20]. This information is consistent with surveys conducted in previous studies in rural communities such as El Espino, El Sena, and Raqaypampa. Community services aim to provide education, good health, and clean water to the population, and common infrastructure for this purpose includes hospitals, schools, drinking water supply systems, and sports facilities. The National Norm for the Characterisation of Primary Health Care Facilities [21]sets minimum criteria for health facilities in rural areas based on the population size and geographic accessibility. Educational facilities need to be accessible to people living in rural communities, but education coverage in the Bolivian lowlands is still low [22]. Three types of educational facilities have been identified in rural areas, depending on the size of the community where those are located.

Income-generating activities (IGA) in Bolivian rural areas are primarily agricultural and livestock-based, with 78% of the employed population working in this sector [23]. 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 [24, 25]. 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

4.1. Key variables

Accurately estimating the demand for electricity in remote areas that lack access to this resource is crucial for devising effective solutions that can facilitate the attainment of both national and global objectives of universal access. This, however, is a complicated undertaking that hinges on specific human factors. 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 data reveals that the variables arranged in descending order of impact on electricity consumption at a residential level are: the geographic location or altitude and the household income.

figure_1-eps-converted-to.pdf

Figure 2: Impact of variables on the electricity consumption

These results are consistent with other studies...

4.2. Specific loads characterization

To characterize and generate specific 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 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 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 [26] was utilized to validate variables that influence electricity consumption.

4.2.1. Residential sector

The Electricity Authority's 2020 Statistical Yearbook [27] 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 [**?**] carried out in Bolivia provides data on the ownership of electrical appliances in households across different regions of the country. Figure 2 illustrates the prevalent electrical appliances used in households in lowlands, valleys, and highlands municipalities, with both high and low levels of poverty. The survey reveals that radios, televisions, and cellphones are the most commonly used appliances in municipalities with low and high poverty, where the majority of rural communities are situated. The usage of refrigerators is greater in low poverty areas in the lowlands than in the highlands, where lower average temperatures are experienced. Moreover, the use of radios, instead of TVs, is more frequent in the highlands and valleys than in the lowlands. Modern appliances are scarcely accessible in high poverty regions, which is also apparent in previous studies conducted in rural communities such as El Espino, El Sena, and Raqaypampa.

To gain an overview of residential electrical consumption, it is possible to calculate electricity consumption ranges that represent general behavior over the course of a year. This can be 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 Table 1, 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.

Table 1 highlights the significant regional disparities in electricity consumption. The harsh living conditions in the highlands result in the lowest consumption rates. Conversely, the valleys have much higher electricity usage than the highlands, typically consuming twice as much across all ECRs. However, it is in the lowlands that the most substantial impact on overall electricity consumption is present, with values almost twice as high as those of the valleys.

These findings emphasize the importance of considering the unique characteristics of different regions when modeling electricity usage in rural communities. By doing so, it is possible to better account for the diverse needs and behaviors of households across the country. In this context, an appropriate configuration of appliances used in RAMP can adequately represent these behaviors, which are in line with those observed from on-site surveys. The details of these inputs as a function of region and income are shown in Table X.

4.2.2. Energy Services Sector

The community services refer to the set of activities aimed at meeting the population's fundamental rights to education, healthcare, and access to clean water. The infrastructure required to carry out these activities, which are prevalent in both urban and rural areas, include hospitals, schools of varying sizes, drinking water supply systems, and sports facilities. The National Norm for the Characterisation of Primary Health Care Facilities [32] establishes a minimum set of criteria for the presence of health facilities in rural areas. For communities with populations ranging between 500 and 1000, a health centre is mandatory. For localities with smaller populations, accessibility is prioritised, and the distance between the health facilities with the lowest and highest resolution capacities should not exceed two hours by car. In addition, communities with populations between 1000 and 10,000 inhabitants should have a health centre with hospitalisation capabilities. The document also outlines minimum infrastructure and equipment requirements for these healthcare facilities.

Through the drafting of this regulation, the government establishes minimum requirements for providing first-level healthcare services. It ensures that conditions are "adequate" based on the characteristics of rural communities, such as their population size and distance from larger communities. Educational facilities should also be accessible to those living in rural areas. Despite recent progress, education coverage in the Bolivian lowlands still ranges from 73% to 83%. This implies that certain rural communities still lack access to educational facilities. The three types of educational facilities prevalent in rural areas include Type A schools, which are small, multi-level establishments located in the smallest and remotest communities. Type B schools are more extensive, with multiple classrooms and levels of instruction from primary to secondary, and they can operate double shifts. Finally, Type C schools are well-equipped establishments capable of accommodating larger student populations.

Table X presents a summary of the electrical appliances considered in each type of user belonging to the community services sector for the RAMP modeling.

4.2.3. Income Generating Activities

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

4.3.1. Community level

The variables of greatest impact defined in the first stage of the study were used as inputs to generate the electricity demands of the communities. In this sense, the structure of the complementary code based on RAMP is shown in Figure 3.

The model, which is based on the RAMP tool, 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), and the proportion of high and low consumption users.

The simulation results of 6 scenarios representing rural communities located in the three main regions (lowlands, valleys and highlands) with different sizes and different proportions of high and low consumption households are illustrated below.

4.3.2. Country level

It is noteworthy that, owing to their large surface area, communities in the lowland zone are more geographically isolated. According to the 2012 census, the valleys and highlands are home to the greatest number of communities that lack access to any form of electricity. Nevertheless, the productive and processing potential is mainly concentrated in the valleys and lowlands.

5. Conclusion

Acknowledgments

The ACADÉMIE DE RECHERCHE ET D'ENSEIGNEMENT SUPÉRIEUR (ARES) is acknowledged for the financial support for this work in the framework of the within the framework of the PRD Tailored energy system models for energy planning in Bolivia (BO2020SIN270).

6. Adding Detailed Explanations

Nomenclature

LL Lowlands,

HL Highlands

VA Valleys

HC High consumption

LC Low consumption

IGA Income Generating Activities

N_{el} net electric power but not with concentration,

$P_{k,el}$ amount of k-th harmful substance burdening the production of electricity.

References

[1] Bisaga I, Parikh P. To climb or not to climb? Investigating energy use behaviour among Solar Home System adopters through energy ladder and social practice lens. Energy Research and Social Science. 2018 Oct;44:293-303. Publisher: Elsevier Ltd.

[2] Ulsrud K, Winther T, Palit D, Rohracher H, Sandgren J. The Solar Transitions research on solar mini-grids in India: Learning from local cases of innovative socio-technical systems. Energy for Sustainable Development. 2011;15(3):293-303. Publisher: International Energy Initiative. Available from: http://dx.doi.org/10.1016/j.esd.2011.06.004.

[3] Riva F, Tognollo A, Gardumi F, Colombo E. Long-term energy planning and demand forecast in remote areas of developing countries: Classification of case studies and insights from a modelling perspective. Energy Strategy Reviews. 2018;20:71-89. Publisher: Elsevier Ltd. Available from: https://doi.org/10.1016/j.esr.2018.02.006.

[4] Riva F, Ahlborg H, Hartvigsson E, Pachauri S, Colombo E. Electricity access and rural development: Review of complex socio-economic dynamics and causal diagrams for more appropriate energy modelling. Energy for Sustainable Development. 2018;43:203-23. Publisher: International Energy Initiative. Available from: https://doi.org/10.1016/j.esd.2018.02.003.

[5] Klaniecki K, Duse IA, Lutz LM, Leventon J, Abson DJ. Applying the energy cultures framework to understand energy systems in the context of rural sustainability transformation. Energy Policy. 2020;137(October 2019):111092. Publisher: Elsevier Ltd. Available from: https://doi.org/10.1016/j.enpol.2019.111092.

[6] Ringkjøb HK, Haugan PM, Solbrekke IM. A review of modelling tools for energy and electricity systems with large shares of variable renewables. Renewable and Sustainable Energy Reviews. 2018;96(August):440-59. Publisher: Elsevier Ltd. Available from: https://doi.org/10.1016/j.rser.2018.08.002.

[7] Trutnevyte E, Hirt LF, Bauer N, Cherp A, Hawkes A, Edelenbosch OY, et al. Societal Transformations in Models for Energy and Climate Policy: The Ambitious Next Step. One Earth. 2019;1(4):423-33.

[8] Krumm A, Süsser D, Blechinger P. Modelling social aspects of the energy transition: What is the current representation of social factors in energy models? Energy. 2022;239:121706. Publisher: Elsevier Ltd. Available from: https://doi.org/10.1016/j.energy.2021.121706.

[9] Herraiz-Cañete Ribó-Pérez D, Bastida-Molina P, Gómez-Navarro T. Forecasting energy demand in isolated rural communities: A comparison between deterministic and stochastic approaches. Energy for Sustainable Development. 2022 Feb;66:101-16. Publisher: Elsevier B.V.

[10] Peña Balderrama JG, Balderrama Subieta S, Lombardi F, Stevanato N, Sahlberg A, Howells M, et al. Incorporating high-resolution demand and techno-economic optimization to evaluate micro-grids into the Open Source Spatial Electrification Tool (OnSSET). Energy for Sustainable Development. 2020 Jun;56:98-118. Publisher: Elsevier B.V.

[11] Spalding-Fecher R, Winkler H, Mwakasonda S. Energy and the World Summit on Sustainable Development: What next? Energy Policy. 2005;33(1):99-112.

[12] Pachauri S, Brew-Hammond A, Barnes DF, Bouille DH, Gitonga S, Modi V, et al. Energy Access for Development. Global Energy Assessment (GEA). 2012:1401-58.

[13] Sanchez C, Betta PD, Stevanato N, Andersen L, Guzmán G, Quoilin S, et al. The Energy Sufficiency Concept and Its Impact on Energy Demand Estimation in Rural Communities from Developing Countries.

[14] Lombardi F, Balderrama S, Quoilin S, Colombo E. Generating high-resolution multi-energy load profiles for remote areas with an open-source stochastic model. Energy. 2019;177:433-44. Publisher: Elsevier Ltd. Available from: https://doi.org/10.1016/j.energy.2019.04.097.

[15] ENDE. Memoria Anual 2018. Empresa Nacional de Electricidad; 2018.

[16] Peña Balderrama JG, Balderrama S, Lombardi F, Stevanato N, Sahlberg A, Colombo E, et al. Incorporating an automated methodology to evaluate mini-grid solutions into the Open Source Spatial Electrification Tool (OnSSET). In Press. 2020.

[17] MDRyT, VDRA. Compendio Agropecuario: Observatorio Agroambiental y Productivo; 2012.

[18] INE, Ministerio de Salud. Encuesta de Demografia y Salud 2016; 2019.

[19] GIZ. Estudio de caracterización sobre el consumo eléctrico en hogares y las potencialidades relacionadas con eficiencia energética; 2020.

[20] INE INdE. Encuesta integrada de hogares 2016- 2017. 2019:545.

[21] Redes de Servicios de Salud y calidad S. Norma Nacional De Establecimientos De Caracterización De Establecimientos De Salud De Primer Nivel. Journal of Chemical Information and Modeling. 2013;53(9):21-8. ArXiv: 1011.1669v3 ISBN: 9788578110796.

[22] Ministerio de Educación. Plan Nacional de Ciencia, Tecnologia e Innovación. La Paz: GENBOOK; 2013.

[23] Jiménez W, Lizárraga S. Ingresos y Desigualdad en el Área Rural de Bolivia. UDAPE. 2003.

[24] Salazar C, Jimenez E. Ingresos familiares anuales de campesinos e indigenas rurales en Bolivia; 2018.

[25] Valencia H, Vera D. Diversificación de ingresos en el Área Rural : Determinantes y Características. Banco Central de Bolivia; 2010.

[26] Andersen LE, Branisa B, Calderón F. Estimaciones del PIB per cápita y de la actividad económica a nivel municipal en Bolivia en base a datos de consumo de electricidad. La Paz: CIS; 2019.

[27] AETN. Anuario Estadístico 2020; 2020.

bluepoli!40 **ECR**	**Highlands**	**Lowlands**	**Valleys**
1st	[0;5]	[0;23]	[0;9]
2nd	[5;13]	[23;54.5]	[9;22]
3rd	[13;28]	[54.5;95.5]	[22;48.5]

Table 1: Yearly electricity consumption ranges [KWh/month]