POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Executive Summary of the Thesis

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

Laurea Magistrale in Energy Engineering - Ingegneria Energetica

Author: Pietro Di Betta

Advisor: Prof. Matteo Vincenzo ROCCO

Co-advisor: Ing.Nicolò STEVANATO

Academic year: 2021-2022

---

1. Introduction

Achieving universal access to reliable, affordable, and modern energy services by 2030 is a key target in the Sustainable Development Goals (SDG 7). However, around 770 million people worldwide still lack access to electricity, with 84% of them residing in rural areas of developing countries. Alternative off-grid solutions like mini-grids are necessary for promoting sustainable development in rural areas, especially when extending the national electricity grid is not feasible due to long distances, high costs, and low energy density. The correct sizing and deployment strategies of these systems are crucial for their success and sustainability. To this purpose, over the last decades Energy System Modelling (EMS) has proven to be a key tool in developing customized off-grid solutions and integrating them into larger electrification plans for efficient and effective distribution. However, the scientific community has long focused on constructing highly detailed supply energy system models and neglected to adequately characterize demand, which represents a fundamental exogenous input for these models. This has led to unsustainable energy systems due to unreliable demand estimations resulting in improper sizing. This issue is especially relevant for long-term energy planning models for rural electrification that rely on aggregated estimations of demand, which may not capture the needs and real dynamics of individual settlements. To develop efficient and sustainable energy strategies, analysing local energy demand based on socio-economic factors specific to each settlement is essential.

On this premises, this study aims to develop a methodology that allows for a preliminary electrical demand estimation, based on the unique needs and context of targeted non-electrified communities, to support the formulation of cost-effective electrification strategies in rural areas of developing countries.The procedure is applied to small rural communities in Bolivia and comprises four blocks, along with a sizing step application.

2. Methodology Description

2.1. First block: electrical demand characterization

The characterization of electrical demand in remote Bolivian communities starts with a re-conceptualization of the energy sufficiency concept. This approach recognizes the inter-linkage between energy and all aspects of community life, including education, health, and social participation. It is tailored to the unique socio-economic factors of rural areas in developing countries and establishes a minimum level of energy services required to ensure dignified living conditions in rural communities, enabling continuous economic and social development. Therefore, the work proceeds with the assessment of basic energy needs in un-electrified communities using a top-down approach, which creates load demand archetypes. These archetypes are designed to replicate un-electrified rural communities based on three main drivers: altitude, poverty level, and community size.

2.1.1 The role of archetypes

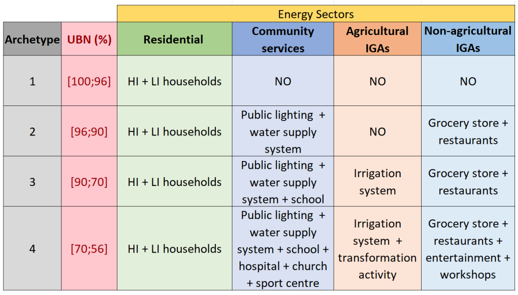
Estimating load demand for communities without prior electricity access and tracking its evolution over time is challenging, especially given the difficulties in gathering data from remote areas. The archetype approach provides a simplified method for quick and easy load estimates, serving as an alternative to more complex and often less accurate load estimation techniques. This methodology can support the identification of suitable locations for electrification planning, where more detailed assessments can begin, enhancing accuracy and efficiency. To account for the various factors affecting electrical demand in Bolivia, the archetype creation process divides the country into three regions based on altitude: highlands (above 3000m), lowlands (below 1500m), and valleys (in between). Altitude has proved to be a crucial driver in determining electrical demand due to its correlations with climate, economic and agricultural activities, as well as social and cultural habits. Poverty-related conditions, as measured by the Unsatisfied Basic Needs index, and community size are also considered as primary drivers impacting community composition and, in turn, total electrical load. The resulting community archetypes are valid at the national level and provide a comprehensive understanding of how different combinations of these three primary drivers impact electrical demand. The proposed archetypes offer an approach to model a community's complete structure, incorporating residential, community services, and Income Generating Activities (IGAs) sectors. Within each sector, different archetypal energy users can be identified, each characterized by a list of appliances and specific activity patterns. Table 1 presents all the defined electrical users, which are used as building blocks for constructing different communities. However, the same user may have different characteristics depending on the altitude range considered. Furthermore, particular attention has been given to the modelling of transformation activities, which are frequently overlooked by traditional approaches.

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

Table 1: Energy sectors, users and users' types.

In addition, to assess the impact of improved electricity access, it was necessary to construct a hypothetical development pathway towards energy sufficiency for rural communities. To achieve this, with the size and altitude of a village fixed, the development process was designed to reduce the levels of Unsatisfied Basic Needs (UBN). Consequently, based on UBN levels, the composition and characteristics of the energy sectors of the community would change, as illustrated in Figure 1. The UBN levels selected for each stage of development are linked to an existing approach used to classify rural Bolivian municipalities. During the analysis, the four stages of development will be referred to as archetype 1, 2, 3, and 4 for simplicity. It should be noted that the fourth archetype represents the energy sufficiency status.

Hence, we create plausible archetypal communities by defining five community sizes (200, 500, 800, 1000, and 1500 inhabitants) for each of the three altitude range: highlands, valleys, and lowlands. For each community size, we explore the four stages of development described previously, resulting in a total of sixty archetypes: twenty for each region. The development of



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

Figure 1: Four community archetypes.

these archetypes was based on a synthesis of various sources, including field visits, literature reviews, and insights from grey literature. Multiple criteria were used to determine the number and types of energy users required to construct the community's structure.

2.2. Second block: Electrical demand assessment

To assess the total electrical demand of each archetype, the RAMP model is utilized [2]. The model employs a bottom-up approach that takes the archetypes as input and generates the annual load curve for each day of the year, producing 365 stochastic daily profiles at a one-minute time resolution. The archetypal user modelling conforms to the requirements of RAMP, which starts with input data on the types of users present in the village, their appliance usage, and patterns. RAMP is specifically designed to handle the low-level accuracy of input data typically found in rural contexts while simultaneously enabling the creation of high-resolution energy load profiles. Analysing the load curve results provides insights into the peak power requirements (kW) and the daily and annual electricity demand (MWh) for each community archetype. Additionally, these estimates are computed for each energy sector of every archetype, enabling to examine each sector within the community separately. First important findings allow to understand the influence of the drivers used for the archetypes creation.

2.3. Third block: validation process.

The third block of our research focuses on validating the residential sector modelling and archetype creation methodology by analysing real data on monthly electrical consumption from across Bolivia. To achieve this, we have two key objectives. First, we aim to evaluate the accuracy of our methodology in predicting monthly residential electrical consumption and identify any discrepancies between predicted and actual data. Second, we will analyse a set of variables that affect residential electricity consumption (e.g., altitude, grid proximity, poverty-related factors). It's important to assess the correlations between these variables and electricity consumption, particularly with the main drivers used to build the archetypes. In fact, if there are no significant correlations, we may need to rethink our methodology for creating archetypes. By achieving both objectives, we can develop a more accurate and reliable modelling of the residential sector and assess the validity of our approach.

2.4. Fourth block: improved methodology

Upon completion of the validation process, we have identified significant discrepancies between the electrical consumption values of real measured data and the ones simulated through RAMP. Consequently, there is the need to remodel the residential sector users. Thus, the fourth block aims to improve the initial methodology approach used for estimating the electrical demand of rural communities by incorporating the insights gained from the validation procedure. Subsequently, we will conduct the same electrical demand analysis (made in block 2) to compare the initial approach with the improved one. Figure 2 shows the flow diagram of all the methodology's four blocks.

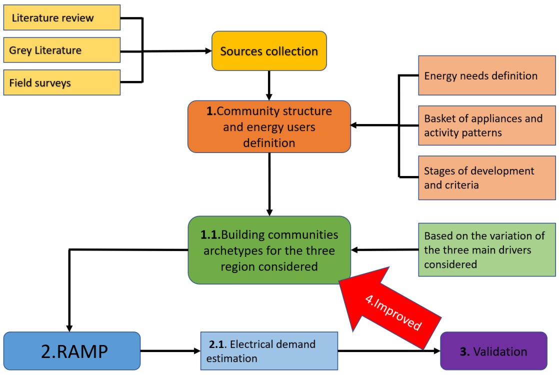


Figure 2: Flow diagram.

2.5. Sizing application

Three rural communities located in different contexts - highlands, lowlands, and valleys - have been carefully selected as case studies to showcase the impact of our methodology on sizing mini-grid systems. To size mini-grids, we will use an energy system model called MicrogridsPY [1], which is a bottom-up linear programming optimization model. MicrogridsPY can perform a two-stage stochastic optimization and will use the RAMP results as inputs for load demand along with an assessment of the renewable energy potential based on the communities' location. The case studies will help us analyse several factors affecting optimal sizing: the impact of altitude, processing activities, and the validation procedure.

3. Results

This section presents the main findings of the overall study often comparing the initial methodology and the improved final version (2.4). We first present the main findings of the validation procedure that led to the residential sector remodelling and subsequently caused differences between the two methodologies.

3.1. Validation results and remodelling

Firstly, to analyse the relationship between selected variables (see 2.3) and monthly electricity consumption, we used Spearman's correlation method to account for potential nonlinear relationships. This method summarizes the strength of the relationship between two data samples. Our findings confirmed that altitude and UBN have a significant impact on residential electricity consumption and archetype creation. Altitude is the primary driver of monthly household electricity consumption variations, with a negative correlation indicating that highlands communities have lower electricity consumption. Similarly, UBN variable shows a negative correlation but with less intensity. An applicative example of correlation scores is shown in Table 2. While we searched for other influential variables to refine the archetype creation methodology, no other significant variables beyond altitude and UBN were identified.

Variables	Spearman Score
UBN	-0.50
Altitude	-0.76
Road Distance	0.04
Number of Electrified Households	0.19
Travel Hours	-0.11
Distance MV 2012	0.29

Table 2: Correlation scores: month of July.

Secondly, we identified three Electricity Consumption Ranges (ECRs) by analysing real monthly electrical consumption data of rural households. Each ECR represents the average consumption behaviour of households with different income levels: low-income in the first ECR, middle-income in the second, and high-income in the third. Table 3 presents this classification, which characterizes the electricity consumption of households in all three regions considered. Consequently, to ensure accurate estimation of monthly electrical consumption values using RAMP, we calibrated the inputs to match the measured data of ECRs for each region and residential user type. This involved varying the number of appliances while using the same basket of appliances selected in the first methodology until the estimated monthly electrical consumption values fell within the identified ranges. We also introduced the middle-income household user to represent the electrical consumption values identified by the 2nd ECR and improve the level of detail in the residential sector transition between low-income and high-income households. The initial methodology only considered high-income and low-income households.

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

Table 3: Yearly electricity consumption ranges.

3.2. Electrical demand analysis

Figure 3 shows the monthly electrical consumption per household across the four archetypes and for all regions obtained from the RAMP model using the improved methodology. The graph highlights the contributions of high-income (HI), low-income (LI), and middle-income (MI) households to the residential load for one month, along with the Dignified Tariff (represented by the red line). This tariff is a Bolivian governmental initiative aimed at increasing energy consumption among low-

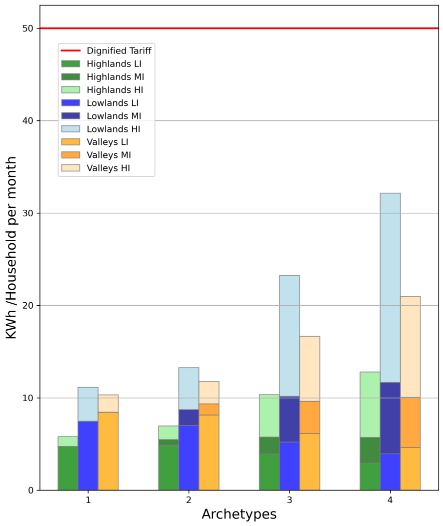


Figure 3: Residential analysis: improved methodology's results.

income households by making electricity more affordable. It offers a discount of 25% to rural households consuming less than 50 kWh/month, which we considered as the threshold for achieving energy sufficiency in the residential sector. Electrical consumption increases significantly as poverty rates decrease, with the fourth archetype consuming at least twice as much as the first. However, compared to the previous methodology (2.2), we observed a significant decrease in electrical consumption growth due to improvements in our approach, such as calibrating residential archetypes using ECRs, introducing the middle-income household user, and implementing a new procedure to determine household numerosity, resulting in halving the number of high-income households.

In contrast to the initial methodology, the improved approach highlights significant regional disparities in electrical consumption that are present from the first stage of development and are observed across all archetypes, increasing towards the final stage. These disparities reflect the different baskets of electrical appliances modelled in RAMP, which were based on validation results (Table 3) and climate regional differences. In fact, the modelling of fridges is highly sensitive to ambient temperature, resulting in variations in consumption across regions. Specifically, the lowlands have the highest consumption due to their high temperatures, the highlands have the lowest due to their cooler climate, and the valleys fall in between. Furthermore, fridges are the most energy-intensive appliance considered, and their presence or absence is crucial in determining electricity consumption levels.

The energy sufficiency status and its achievement requires a linked discussion as no residential sector in any region meets the Dignified Tariff's threshold. Stronger disparities in electricity usage arise when we consider the single residential user types, rather than the sector average, as done in Figure 3. HI households, for example, exceed the sufficiency threshold in the lowlands, consuming 87KWh/month, but the same residential user type never reaches these values in the highlands, consuming less than 50KWh/month. This raises a crucial issue: while households across different regions meet the same basic needs, the strong reliance of refrigeration on temperature leads to a notable increase in overall electricity consumption. However, this increase does not necessarily improve living conditions. Therefore, adjusting sufficiency thresholds to account for regional variations can be beneficial. This highlights the limitations of using nationwide electrical consumption standards for an entire country.

3.3. Yearly electricity consumption: break down per energy sector

Figure 4 presents a detailed breakdown of the energy sector's contributions to the yearly electrical consumption of a highland community comprising 500 inhabitants. The results indicate that after remodelling, residential consumption significantly decreased, resulting in the lowest percentage contribution compared to other regions. Consequently, the contributions of other sectors increased, even if the IGA and community services sectors remained unchanged. In the fourth archetype, residential consumption accounted for 44% of total electricity consumption, which is comparable to the IGA sector's consumption. Remarkably, the total consumption at the community level declined by nearly 50% for all archetypes compared to the previous methodology's values.

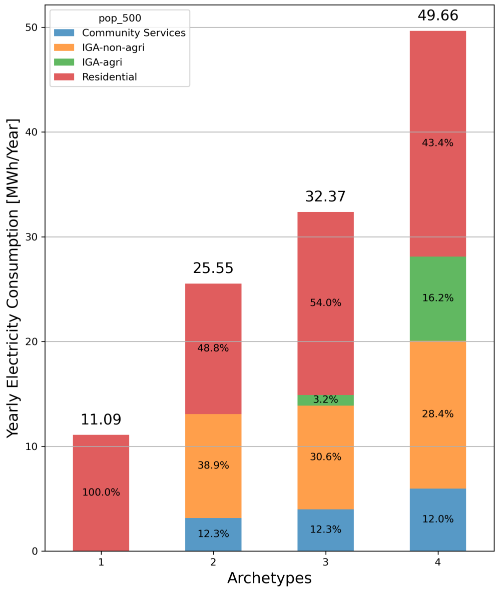


Figure 4: Consumption break down per energy sector: improved methodology's results.

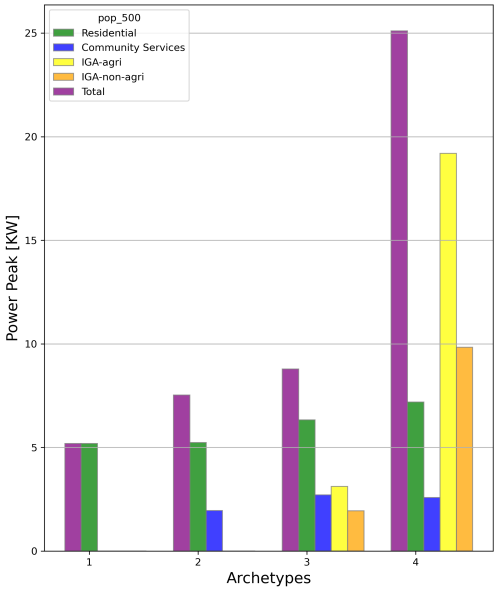


Figure 5: Peak power analysis per sector: improved methodology's results.

3.4. Peak power per energy sector

Figure 5 shows the peak power analysis of a 500-inhabitant highland community. The remodelling has resulted in a decrease in residential sector values for all archetypes, leading to reduced community peak power values. This is a significant change from prior findings where residential peak power would double as the community progressed from the first to the last archetype. Moreover, when the community achieves energy sufficiency (fourth archetype), the IGA sector surpasses residential peak power with a larger gap between the two compared to the initial methodology. This is largely due to the introduction of transformation activities that involve energy-intensive machinery.

3.5. Sizing main results

Firstly, altitude has proved to play a crucial role in determining the optimal size and thus appropriate energy deployment strategies for mini-grid system. In fact, the difference in Net Present Cost (NPC) between lowland and highland systems can be as high as 63%. Secondly, adopting the improved methodology significantly reduced the NPC of the systems by up to 64%. Lastly, while the inclusion of processing activities in a mini-grid system may lead to a 17% increase in NPC, it can also bring substantial benefits to the community's development without affecting the cost of electricity for the end customers. Therefore, it is essential to conduct a comprehensive analysis that takes into account all relevant factors to make an informed decision on the feasibility and deployment of a project.

4. Conclusions

This study has revealed that altitude, community structure, and UBN are key factors impacting the electrical demand curve in rural communities. Therefore, failing to account for heterogeneity within a country could result in inaccurate predictions of electricity demand, hindering the development of effective energy strategies. Moreover, the adoption of energy-intensive appliances plays a vital role in the variability of electrical demand. For instance, the acquisition of a refrigerator by a specific residential user type in a particular area can have a significant impact on the electricity required to meet their basic needs. All these aspects have highlighted the limitations of using nationwide electrical consumption standards for an entire country, as such standards often fail to account for the diverse needs and circumstances of individual regions. Additionally, results demonstrated the need for policymakers and energy planners to consider the IGA sector's electrical demand. Neglecting this sector can result in significant energy deficits, hindering the community's economic growth and development. In conclusion, this research study has established the pressing need to focus on characterizing electrical demand and its pertinence in Bolivian rural areas. It has been highlighted the importance of accurately assessing load demand for effectively modelling energy system solutions, which can lead to cost savings, improved energy strategies, and increased sustainability of the assessed systems. Furthermore, the proposed methodology is meant to be flexible with the ability to adjust to changes in electrical demands, making it reusable in other contexts and countries.

References

[1] Sergio Balderrama, Francesco Lombardi, Fabio Riva, Walter Canedo, Emanuela Colombo, and Sylvain Quoilin. A two-stage linear programming optimization framework for isolated hybrid microgrids in a rural context: The case study of the "el espino" community. *Energy*, 188:116073, 2019.

[2] Francesco Lombardi, Sergio Balderrama, Sylvain Quoilin, and Emanuela Colombo. Generating high-resolution multi-energy load profiles for remote areas with an open-source stochastic model. *Energy*, 177:433–444, 2019.