Load Profile Reconstitution for the Design of Hybrid Systems

Application for rural electrification projects in mini-grid environments

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Abstract—**Hybrid systems based on renewable energy are becoming a common solution for providing electricity to remote villages for rural electrification projects.**

One fundamental input parameter for designing a technically sound and cost-optimized hybrid system is to know the electrical demand to be met, which includes not only the quantity of electricity, but also the power requirements with hourly profiles and seasonal variations. This is of high importance to avoid over or under sizing the system components and to select the optimum technology according to the available renewable resources.

This paper presents an approach to construct hourly load profiles based on three steps: (i) an extensive site survey in the village to be electrified, (ii) user categorization and definition of typical load curves per category, and (iii) reconstitution of the global load profile at village scale. In order to reduce the uncertainty of the reconstituted load curves, adjustment factors are defined to consider additional parameters, such as the willingness to pay for electricity and the comparison with existing consumption figures in similar environments.

Along with the description of the methodology, results from a case study are presented for each step. This case study is based on real project experience from Tractebel Engineering GmbH, which acts as technical advisor and consultant to several governmental rural electrification agencies in West Africa.

Keywords: hourly load profile, hybrid system design, rural electrification, mini-grid, energy-use survey, electrical demand

I. INTRODUCTION

Mini-grids powered by hybrid systems based on Renewable Energy (RE) are becoming a common solution to provide electricity to remote villages for rural electrification projects. These RE-based systems enable reduction in fuel dependency compared to traditional diesel genset operation and provide a lower levelized cost of electricity provided that the sites have sufficient resources, such as solar irradiation and wind. This trend continues to be strengthened with the significant cost reduction of photovoltaic technology over the last 10 years and the on-going cost decrease in energy storage systems.

One fundamental input parameter for designing a technically sound and cost-optimized hybrid system is to know the electrical demand to be met, which includes not only the quantity of electricity, but also the power requirements with hourly profiles and seasonal variations. This is of high importance to avoid over or under sizing the different system components, especially for hybrid systems including RE and storage technologies which both still require significant capital expenditure (CAPEX) compared to the diesel scenario. Indeed, on one hand, an oversized generation capacity would result in an inefficient use of CAPEX and poor economic performance for the mini-grid operator. On the other hand, if load to be served is underestimated, the reliability of the power supply will not be ensured, leading to energy and capacity shortages.

II. MOTIVATION

For rural electrification projects located in remote locations, it is likely to encounter one of the two following situations: (i) either the village under study has no access to electricity, or (ii) the village is electrified but the power supply is unreliable and most likely interrupted throughout the day.

In both cases, the electrical demand cannot be directly estimated from the existing and historical consumption data. As a result, there is a need to define a coherent approach to estimate the energy demand and to construct the hourly load profiles at the village scale. The common practice is the so called "end-use method" or "energy-use survey" which assesses the electrical demand based on interviews with future users and collected data on appliances and foreseen daily usages. Previous studies ([1] Hartvigsson et al. 2018 and [2] Blodgett et al.) have shown significant discrepancies between the electrical demand estimated from energy-use surveys and field measurements. Reference [2] concluded that the respondents overestimated their actual usage, with an average error more than three times the actual consumption. Reference [1] demonstrated that energy use was also largely overestimated in the survey results for small and medium enterprises whereas for domestic use measurements showed a night load seven times higher than the estimated value from the survey and a morning peak demand which was not reflected in the survey. Evidently, there are many parameters which potentially explain the differences between estimated load profiles from energy-use survey and real consumption figures, amongst others: inherent bias introduced by the interview approach (questionnaire formulation, interviewer bias and data analysis), electricity tariff and ability/willingness to pay, electricity payment scheme (flat rate or kWh based), uncertainty on appliance power ratings and usage hours for users with no electricity experience to date.

The objective of this paper is to present an approach for estimating the electrical demand and hourly profiles at the village scale for sites without historical consumption data. This approach is based on three steps: (i) an extensive site survey in the village to be electrified, (ii) user categorization and definition of typical load curves per category, and (iii) reconstitution of the global load profile at the village scale. This approach also aims to consider additional parameters, such as the willingness to pay for electricity and the comparison with existing consumption figures in similar environment in order to reduce uncertainty of the reconstituted load curves.

For each step of the proposed approach, the results of a case study are presented. This case study is based on real projects carried out by Tractebel Engineering in West Africa. Tractebel Engineering GmbH (formerly Lahmeyer International) has gained comprehensive experience worldwide in the field of rural electrification and hybrid systems, in particular as technical advisor and consultant to several governmental rural electrification agencies.

III. APPROACH

This section describes in more details each step of the proposed approach and presents the main outcomes of the case study in table and graph format.

A. Step 1: Site survey and data collection

It is not the intention of this paragraph to provide an extensive guide, methodology and questionnaires to be used for the survey; the objective is to highlight the key parameters and criteria to be collected and analyzed. Detailed recommendations to conduct site survey can be found in [3] NRECA'S technical assistance guides and in [4], Decentralized Rural Electrification (Christophe de Gouvello and al.). The outcome targeted by the survey is to get a representative overview of the village to electrify regarding the demographic and geographic configuration, the present and projected socio-economic activities and the total quantity of households. In addition, results shall include for each identified user category the typical electrical appliances and their envisioned daily usage profiles as well as an assessment of the willingness to pay (defined as the maximum amount that a user is willing to pay for electric services).

1) Socio-economic environment survey

Meeting with the local authorities (e.g. mayor, chief of the village) and associations enables to understand the socio-economic environment of the village and to identify the quantity and type of future users. It is then necessary to prepare an inventory of the total quantity of households and all existing community-based infrastructures (schools, health-post, religious centres, associations, etc.), commercial applications (grocery shops, bars, restaurants, sewing workshops, hairdresser salons, etc.), and productive applications (welding workshops, cereal grinders, mills, water pumps, etc.). Commercial and productive applications are defined as applications generating income for the users, with higher power requirements for the productive applications.

TABLE I : SOCIO-ECONOMIC SURVEY (CASE STUDY)

Village Description	Rather large size (12,000 inhabitants) with substantial economic activities and important administrative role in the area
Population growth (1998-2009)	3.1 %/year
History with regard to electrification	Electrification in 2010 with a diesel-powered mini-grid with the target to provide electricity four hours per day. At the date of the survey (2016), the existing power plant was only providing electricity sporadically (a few days per week) due to technical and operational limitations.
Total quantity of households	2,000
Households connected to the existing diesel power plant	365
Existing* Community-based infrastructures	2 health posts 1 maternity 1 rural development centre 1 training centre 12 administrative offices 3 pharmacies 12 schools 10 religious centres
Existing* Commercial applications	10 sewing workshops 22 shops 12 bars and restaurants
Existing* Productive-use	3 welding workshops 1 carpentry 1 bakery 6 mills 1 water pump
*likely to be connected to the future hybrid power plant	

2) Energy-use survey and willingness to pay study

The energy-use survey aims to evaluate what will be the typical daily consumption based on the electrical appliances and the time of use envisioned by the future users.

In this regard, meetings with the local authorities shall also include discussions on the desired strategy for public lighting: quantity and type of light bulbs as well as the time of use and payment mechanism.

Besides meeting with the local authorities, it is important to carry out representative samplings of field visits and questionnaires for each of the potential user categories previously identified. Field visits have the objective to list typical electrical appliances and their power ratings which are envisioned to be used once the electricity supply is effective. Daily foreseen usages of each appliance (how many hours and at which time of the day) and opening times for commercial and community-based applications shall be recorded. It is of high importance to crosscheck that the appliances listed within the survey are effectively available in the project area. Although, it is obviously relevant to promote the use of energy efficient devices, experience shows that second-hand appliances (with consumption figures often on the high range) remain common in such rural environments.

Special attention is also required to evaluate the seasonal effects in the energy demand and power consumption. These effects can be substantial for locations with high temperature differences along the year and seasonal economical activities (e.g. harvest periods, fishing season). Differentiation between weekdays and weekend days shall also be reflected in the survey results.

One part of the questionnaire shall be dedicated to the assessment of the current monthly expenditures for energy services. Within these actual expenditures, it shall be determined what is the share which can be replaced by electricity (e.g. candles for lighting, batteries for radio, etc.). This parameter coupled with direct questions to the interviewees shall serve to estimate the Willingness to Pay (WTP) for electric services, which is expressed in local currency per month. The preparation of structured questionnaires suitably adapted to the local context and the training of the surveyors are key to limit the sources of error and ensure the proper data collection and processing. Reference [3] provides guideline for conducting such survey and WTP study.

TABLE II : ENERGY-USE SURVEY AND WTP STUDY (CASE STUDY)

	Category	Appliances
Typical appliances, quantity and power ratings	Households	• 8 Fluorescent lamps (15 W, 6 hr/d) • 3 fans (65 W, 6 hr/d) hot season • 1 TV + antenna (100 W, 4 hr/d) • Fridge (75 W, for 25% HH) • 5 Mobile chargers (5 W, 6 hr/d)
	Community-based infrastructures	Depending on type of infrastructure, the following are found: • Sound system (150 W) • Fluorescent lamps (15 W) • Fans (65 W) • Computer (150 W)
	Commercial applications	Depending on type of application, the following are found: • Computer (150 W) • Laptops (80 W) • DVD+TV (120 W) • Fan (65 W) • Fluorescent lamps (15 W per unit) • Sound system (150 W) • Fridge/ freezer (200 W) • Sewing machine
	Productive use applications	Depending on type of application, the following are found: • Grindstone (2 kW) • Mills (3 kW) • Drilling machine (2 kW) • Water pump (3 kW) • Welding iron (3 kW)
	Note: Average usage times per day other than for households are not shown in the table as they are very dependent on the type of application. Average values are considered at a later stage for the definition of the typical load curve for each category	
Willingness to Pay (WTP)	Households (HH)	WTP ≥ 15 EUR/month for 25% of HH WTP ≥ 9 EUR/month for 50% of HH WTP ≥ 6 EUR/month for 75% of HH

3) *Input from the future Operator*

The quantity and type of the future users to be finally considered for the design stage shall also be determined in coordination with the entity who will be in charge of the operation of the future hybrid system (the “Operator”). Depending on the institutional framework and local conditions, the Operator can be a community-based organization, the national utility or a private company. According to its nature, the prioritization of future users might differ with significant impact on the global load to be met by the hybrid system.

In all cases, the involvement of the future Operator is of high importance at this stage. Indeed, the quantity of connections to consider for the load estimation is also depending on the electricity tariff and payment scheme proposed by the Operator to the population. As commonly recognized and highlighted in [2], financial viability of mini-grid projects is crucial to ensure that the future system can be operated on a long-term perspective. Tariff collection and electrical demand are essential inputs to the Operator’s business model, which implies that the global load demand shall match with the Operator assumptions and objectives in terms of quantity and type of user connections.

It shall be verified that the route of the electrical distribution network to be implemented is defined in such a way that all potential users considered in the business plan have physical access to the network, according to their geographical locations. In this regard, the site survey shall also assess the geographical distribution of housing and economical centres within the village to electrify.

TABLE III : INPUT FROM THE FUTURE MINI-GRID OPERATOR (CASE STUDY)

Type of Operator	Private
Institutional framework	Public-Private Partnership (20 year contract) with subsidy on investment costs in such a way that targeted electricity tariff defined by public authority ensures reasonable financial viability of the Operator
Targeted tariff	0.20 EUR/kWh
Low voltage distribution network	10 km existing 3 km extension planned to reach more users

4) *Projection of the electrical demand*

It is also essential to capture within the site survey how the locality is likely to develop on a 5-year timeframe horizon in order to consider any future significant loads, if any. This projection is a difficult but relevant exercise as the load assessment aims in fine to design a hybrid power plant with a technical lifetime of at least 15 years. Historical consumption data from electrified village(s) in the project surroundings are often a good indicator to estimate how the electrical demand develops once the village gets electricity access. Population growth rate (obtained from past census) might serve as a trend indicator of the village dynamism and attractiveness.

One other indicator to evaluate the future demand is the penetration rate which can be defined as the quantity of households to be connected on the first year divided by the total quantity of households, as assessed during the socio-economic survey. This might help to get a picture of the potential quantity of new users to connect in the future. The Operator can also use this information as input for its business model and expansion plan, keeping in mind that connecting more users might require extending the distribution network, according to the geographical distribution of households.

The expected electrical demand growth is generally expressed in percentage per year and can be broken down into two contributions for each user category: the increase of the quantity of user and/or the increase of specific consumption per user. It is unlikely that these two factors are directly collected during the site survey, but information collected shall help to define solid assumptions which are required at the design stage.

5) Assessment of neighbouring electrified villages

To support and potentially adjust the results of the energy-use survey and the projection of the electrical demand, it is recommended to identify electrified villages in the project surroundings, ideally with similar demographic characteristics and disposable income. Indeed, for comparison and validation purpose, a field visit to these electrified villages would allow to introduce corrections on the potential appliances likely to be used in the village to electrify (especially in case the village has no prior electrical access). Indicators such as monthly energy consumption and peak power demand per user for each category as well as the review of the historical operational data since the installation of the power plant would give precious information for comparison and adjustment purposes.

TABLE IV : NEIGHBOURING ELECTRIFIED VILLAGE (CASE STUDY)

Type of village	One large electrified village (25,000 inhabitants) with a running diesel power plant was found in the project area (85 km from the village under study)
Electrification technic	Electrification via a diesel power plant installed in 2007 which delivers electricity 18 hours per day (from 8 am to 4 pm and from 6 pm to 5 am) to 1,025 users
Socio economical context	Subprefecture with important administrative offices and rather high economical activities
Consumption indicators	Production data was provided for a full year (2016) by the operator, following indicators were calculated: • Energy per user: 2.4 kWh/day (18 hours/day) → 2.8 kWh/d (corrected to 24 hours/day) • Peak power per user: 0.23 kW No historical production data from the start of operation was provided

B. Step 2: User categorization and typical load curve

Once the database is created based on the compilation and analysis of the data collection and site survey results, the second step of the proposed approach consists in defining the user categories and their typical daily load profiles.

Categories are defined based on the expected similarities in the power range and daily usage (time and duration) of electrical appliances. Although tailor-made categories can be defined on a project basis to comply with specific needs or applications, the experience shows that in most cases, the users in rural areas can be classified into the following five categories:

- Category 1: Domestic demand (households). This category is usually the most important one in terms of quantity of users and can be broken down, if necessary, into sub-categories according to the WTP study results;
- Category 2: Community-based infrastructures (e.g. schools, health-posts, religious buildings, administrative offices, associations, etc.);
- Category 3: Commercial applications (e.g. grocer's shops, bars and restaurants, sewing shops, hairdressing salon, etc.);
- Category 4: Productive use (e.g. welding workshop, carpentry, mills, water pumps, etc.);
- Category 5: Public lighting. This category can be disregarded in case of use of solar street lights which is an observed trend in rural areas.

Additional categories can be further defined to meet specific project requirements. Indeed, there might be a need in some cases to define a category for a special load with high power and energy requirements. This was for example the case in one project carried out by Tractebel Engineering GmbH in a coastal fishing village where two base loads were foreseen for the village, namely a desalination plant and an ice production facility for fish preservation.

Based on the analysis of the information collected during the site survey on the appliance type and expected usages, a typical load curve is prepared for each user category with the aim to represent the expected average hourly load profile. Especially for categories 2, 3 and 4, it is a difficult exercise to define such typical load profiles as two users of the same category will most likely not have the exact same appliances and same hourly behaviour with regard to the use of electricity. Therefore, the daily energy consumption was almost uniformly distributed during the opening hours. Hourly values shall be understood as average values, additional variability factors are added at the last step of the process to make the global load curve more realistic, in particular regarding peak demand requirements throughout the day. Peak demand is one important parameter in selecting the generation capacity of hybrid systems at design stage.

1) WTP as adjustment factor

It is recommended to consider the WTP as an adjustment factor when defining the typical load curves. Indeed, this adjustment aims to adapt the outcome of the energy-use survey to the amount of electricity that the future user will be able and willing to pay for. The objective is to avoid an overestimation of the future electricity consumption which would be based only on the energy-use survey. This adjustment factor based on the WTP study results is mainly valid for the domestic demand (category 1) which represents in general the majority of the future consumption in rural environment. In addition, the WTP study is generally conducted on a representative sampling of households and not on other user categories which might experience various revenue sources and levels according to their activities. For example, the community-based infrastructures WTP is very much project specific and depends on the national/regional organization context (e.g. governmental participation to operating budget of schools and health posts) and local environment (e.g. non-governmental organizations). Commercial and productive use applications (categories 3 and 4) are supposed to generate revenues partly thanks to the electricity use. Although it is expected that the financial situation of these professional users presents significant discrepancies, higher consumption figures than values derived from the household WTP are expected.

Finally, public lighting is often viewed as an important application when electricity arrives first in a village. The question of the cost coverage for public lighting shall be raised at design stage with the future Operator and the village authority, as the longevity of the public lighting service depends directly on this cost coverage scheme. A common practice consists in distributing this cost amongst the electricity users with an additional charge on the electricity tariff. Solar street lights and efficient lighting bulbs are practical solutions which are implemented to reduce this additional operating cost for the final users.

2) *Case study results*

In the case study, the WTP has been used as an adjustment factor for the domestic demand only. Energy-use survey for domestic demand resulted in a daily consumption of 2.4 kWh/d for households without fridge and 3.3 kWh/d with a fridge (25% of the interviewees) whereas WTP study and targeted tariff revealed that the daily consumption per user would rather range from 1 kWh/d to 2.5 kWh/d. Consequently, three subcategories have been defined for the domestic demand as described in the table below.

TABLE V: DOMESTIC DEMAND ADJUSMENT AS PER WTP (CASE STUDY)

Category	**Share**	**WTP per user**	**Daily consumption per user**
Category 1-S: Small	25%	6 EUR/month	1.0 kWh/d
Category 1-M: Medium	50%	9 EUR/month	1.5 kWh/d
Category 1-L: Large	25%	15 EUR/month	2.5 kWh/d

The following curves are presenting the typical hourly load profiles generated for each category considered in the case study.

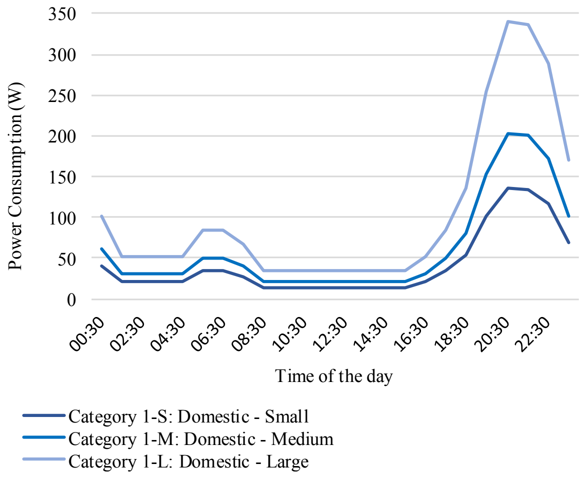

Figure 1. Typical hourly profiles for categoriy 1 (adjusted as per WTP)

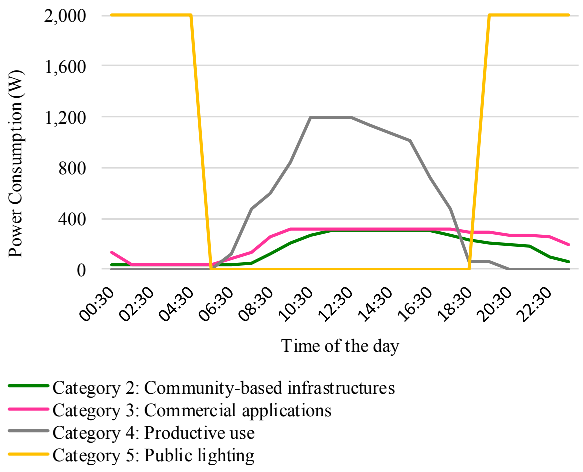

Figure 2. Typical hourly profiles for categories 2, 3, 4 and 5

C. *Step 3 : Reconstitution of the global load profile*

This last step aims to construct the global hourly load profile at the village scale, which shall serve as input data for the design of the hybrid power plant. This global load curve, also defined as the Design Load is then built-up based on the quantity of users to be considered for each category (defined from information collected during Step 1) and the typical hourly load profiles for each category defined in Step 2. In order to consider the electrical demand growth assessed within Step 1, it shall be decided at which year the design of the hybrid system shall be prepared. Indeed, as the load is supposedly increasing over the years once the access to electricity is provided and because the design lifetime of a RE-based hybrid power plant is 15 years+, it is common practice to define the Design Load at year 5. This enables to avoid energy and capacity shortages in the first years of operation while preventing to unreasonably oversize the components in order to cope with an increased future load. This approach is not needed when the modelling tool allows to run yearly simulations over the project lifetime to account for annual load increase and component degradation over time.

In addition to compiling data from Steps 1 and 2 using an Excel-based tool, Step 3 also considers the two following additional factors to generate the Design Load:

- Technical losses to account for distribution losses (cables, transformers) between the future hybrid power plant location and the final point of connection on the end-user. This is necessary as the load has been defined from the needs collected at the user level;
- Non-technical losses to account for potential fraud activities. This parameter can be determined according to experience from electrical operators in the project area and similar environments. This parameter can also be set to zero assuming that the project will not suffer from such loss.

Once the Design Load is generated, the average daily energy consumption and peak demand per user are calculated and compared to values for similar environments identified within Step 1. If energy consumption values per user are found to be within an acceptable range, it brings an additional confidence factor in the obtained Design Load. This comparison on energy consumption per user is especially relevant when there is a very good match on the socio-economic context between the two villages and that the operators are the same entity. In this case, the comparison can be used to further adjust the typical load profiles during Step 2. It can then be considered as a second level adjustment factor, after the WTP.

In case of significant discrepancies in energy consumption figures per user, it is recommended to conduct investigations to find out the origin of the differences (finer analysis on the socio-economic context of the two villages, etc.) and if needed to make an iteration process with Steps 1 and 2.

TABLE VI : ENERGY CONSUMPTION FIGURES PER USER (CASE STUDY)

Parameter	**Design Load (village under consideration)**	**Existing load data (neighbouring electrified village)**
Energy consumption per user	2.5 kWh/d	2.8 kWh/d
Peak power per user	0.25 kW	0.23 kW
The differences observed are in the acceptable range, considering the higher quantity of economical activities in the already electrified village.		

The graph below displays the Design Load at year 5 (including 5% technical losses).

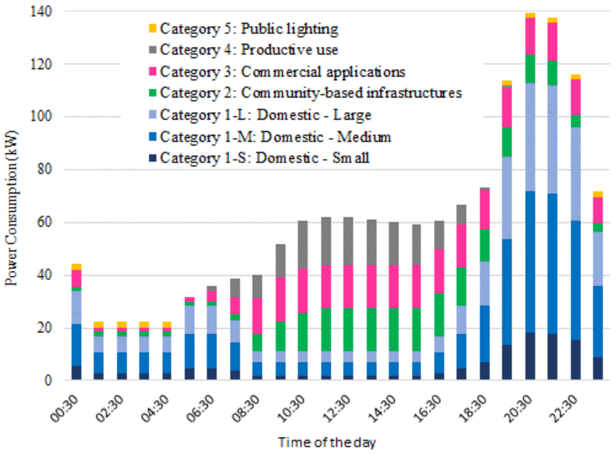

Figure 3. Design Load hourly profile (annual average at year 5)

To add randomness to the Design Load and make it more realistic on a daily basis for annual simulation purposes, it is common practice to include additional factors to take into account inter-day and inter-hour variations. Simulation tools for hybrid systems such as Homer Pro [5] offer this possibility with the day-to-day and time-step-to-time-step variability factors. These factors represent the standard deviation for each criterion (assuming a normal distribution with a mean of zero) and enable to create more realistic-looking load data. This can be shown on the graph below which displays the Design Load curve for different days of the year, using a value of 5% for each of the two variability factors.

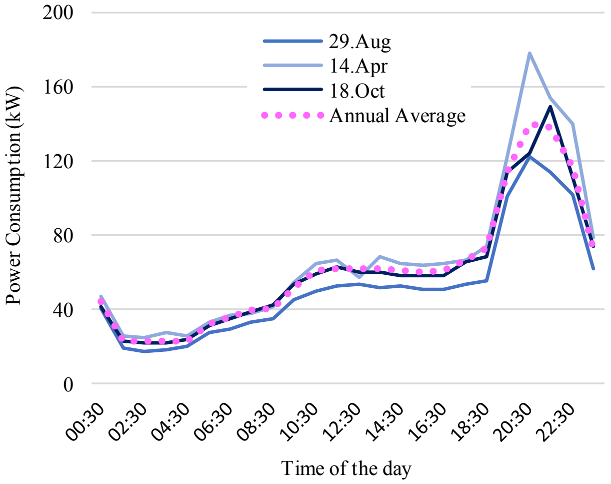

Figure 4. Design Load with application of variability factors

It shall be noted that these variability factors have an impact on the hourly maximum peak load over the year. Indeed, although the annual average peak load remains the same as the Design Load, the application of the variability factors implies that on some days of the year, the peak load can be up to 20% higher than the average annual value average, as can be seen in Fig. 4.

IV. CONCLUSION

This paper gives a guideline to reconstitute the hourly load profiles at the village scale to be used as input parameters for hybrid system design. In order to reduce uncertainty on the reconstituted load curves, this approach proposes to rely not only on the energy-use survey but to also consider adjustment factors based on the willingness to pay study and comparison with similar electrified villages in the project area. Trained surveyors and structured questionnaires to the relevant stakeholders are key for the site survey in order to limit the bias in the data collection and analysis. Understanding the strategy of the future system operator is also important as it can significantly impact the final load to be served and the electrical demand projection. Despite the efforts to reduce the load uncertainty, an accurate load profile estimation remains a challenging task in such rural environments. It is therefore recommended that the hybrid system is designed with a modular concept which allows to adjust the component sizes with limited impact in case of load discrepancy between the actual and Design Load.

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