LOW VOLTAGE ELECTRIFICATION APPROACH IN RURAL AREAS: ARBITRATION BETWEEN ON AND OFF-GRID SOLUTIONS

Mehdi OTHMANI
Engie – France
Mehdi.othmani@engie.com

Ibrahim ABADA
Engie – France
Ibrahim.abada@engie.com

Léa TATRY
Engie – France
lea.tatry@engie.com

Tanguy PORT
Tractebel – Belgium
tanguy.port@tractebel.engie.com

Gauthier ROIG
Tractebel – Belgium
gauthier.roig@tractebel.engie.com

Midas CAUBERGS
Tractebel – Belgium
midas.caubergs@tractebel.engie.com

ABSTRACT

In the context of the SE4all objective to achieve universal electricity access by 2030, power sector stakeholders are looking for low-cost and sufficient-quality electricity supply solutions. At low voltage (LV) scale, in some isolated rural villages, individual solutions such as solar home systems (SHS), solar lanterns or isolated generators can be economically feasible compared with electricity network connection and are considered as efficient temporary solutions to reach the defined target [1]. The proposed paper presents a new optimization methodology developed to evaluate the best electrification solutions at LV scale within villages, combining both the grid reticulation and the individual solutions for the potential customers. In this matter, the optimization minimizes the total cost of electrification of the concerned villages while using intensively the geospatial dimension.

LOW ELECTRICITY ACCESS IN RURAL AREAS AND ELECTRIFICATION STRATEGY

The United Nations pledged in 2012 to provide universal access to electricity by 2030 with the SE4ALL initiative. Five years after, in 2017, 1.1 billion people still lacked electricity access according to the International Energy Agency, among which about 84% live in rural areas and 95% in Sub-Sahara-Africa and developing Asia, indicating the need of a focus on electrifying the rural areas [2]. Furthermore, according to the New Policies Scenario of the International Energy Agency, the electricity demand of the residential sector will grow by 6% per year to 2040. The main drivers for this electricity demand are lighting, cooling (fridges, freezers), access to information (radio, TV, internet) and communication (mobile phones), clean cooking and appliances, with rising incomes funding the purchase of these appliances [3]. To provide everyone with electricity access and supply the increasing demand, generation assets and electricity grids must be expanded and reinforced both on transmission and distribution levels.

At low voltage (LV) scale, economic and technical constraints, such as important grid infrastructure costs for rural households, overloads and voltage drops, constitute a considerable obstacle for fast and large-scale electrification. In some villages, the "last-mile connection" often represents an important additional cost: off-centre loads such as remote customers, irrigation systems, mills, etc. cannot structurally be supplied by an existing LV network or mini-grid with a sufficient quality of service at middle term (15 years). In these cases, individual solutions such as SHS or isolated generators can be economically feasible compared with LV network connections and are considered as efficient temporary electrification solutions. Being able to estimate and optimize the cost to electrify a remote village and to optimally design the grid at the local level will certainly be of paramount help in reaching the rural electrification objectives. This paper presents a new methodology to do so, based on GIS data and some field information about the concerned village(s).

LOW VOLTAGE ELECTRIFICATION TOOLS

Existing tools

Several initiatives have been developed for the design of LV networks. Most notable examples are GEOSIM's GISELEC module [4] and LAP software [5]. Both can offer a detailed LV network design for a group of villages but have high computational costs. This limits the tools from providing a quick and effective solution for an entire region or country. Furthermore, these tools are not able to provide a techno-economical arbitration between LV network and individual solutions such as SHS.

Presented tool

Tractebel is currently developing methodologies for rural electrification planning, among which one is dedicated to the arbitration between the on-grid and off-grid electrification solutions at the regional (medium voltage) scale. This methodology was presented in CIRED 2018 [6]. The developed tool was enhanced by adding a new methodology that allows calculating and optimizing the cost, size and shape of the optimal power grid at LV scale in a given village, considering individual solutions as well.

Goals of the tool

In a nutshell, the tool presents the following features:

(i) Providing a load forecast at the building level by mixing GIS and field information about the buildings of a village. By automatically recognizing the roofs and their properties (surface, shape, material, etc.) on aerial images, the tool strives to predict the potential consumers in the village, as well as their load, using standard machine learning techniques. Additional constraints such as the households specific needs and ability to pay, or the minimum required levels of quality and service, can be included in this procedure to determine the most appropriate solution for each customer.

(ii) Performing a techno-economical optimization of the LV grid and individual solutions such as SHS to install equipment to meet the forecasted demand at least cost. In particular, this step performs the optimal sizing and design of the LV network, including the required medium-to-low voltage transformers, the length of the LV network, the needed PV/battery and diesel generators capacity in case of microgrids with local power generation.

Load forecast at building level

Forecasting the load in remote rural villages can represent a challenge inasmuch as many potential future consumers have never consumed electricity. Furthermore, affecting a load to each building of the village is not an easy task, since the type of building (and thereby the type of consumer and its consumption level) is hardly identifiable based on aerial images. Though, there is a need to estimate the load as precisely as possible, since this input leads to a better suited sizing of the grid: overinvestments can drastically increase the cost of electrification, while under-investments may harm the grid security. As an example, for a typical 30 kW mini-grid with an expected 10.5% IRR (achieved when the grid is correctly sized), oversizing the LV grid by 50% will reduce the IRR to 5.8% (1.5% for a 100% oversizing) [7]. In order to automatize the load forecast process, tests were performed to conclude whether some GIS information of the village, combined with its economic level, gave reasonable indicators that can assist predicting the load. For that sake, a machine learning algorithm was developed, striving to assess the consumption based on the GIS and economical information of the village.

***Inputs**:*

Using aerial images of a village, the number of buildings and their areas are extracted. From these, additional relevant variables are calculated: a remoteness indicator, being the distance of each house to the centre of the village, and a density indicator for each building, which is the number of other houses within a given radius. Those data are combined with the economic level of the village and field survey data if available.

An internal training set of villages that have already been electrified and for which the load of each building is known is provided to enrich the algorithm.

***Principle**:*

An unsupervised learning (clustering) of data is performed to identify the typical profiles of consumption in the training set, corresponding to the different usages of electricity one can find in such villages (light bulbs, productive machines, etc.).

A classification algorithm with regularization is used to explain whether a given household will consume electricity once the grid is installed, and to which typical cluster of consumption it will belong. The regularization procedure has been included to avoid an overfitting of the algorithm that could be caused by any small number of observations in the training set.

Outputs:

Given a new village, the algorithm is able to forecast quite accurately the number of potential consumers, to locate them, and to estimate their load.

***Future work**:*

All the above-mentioned steps of the load forecast are fully automatized, except the roof recognition phase from the aerial image of the village. Thus, efforts are currently provided to develop an approach also exploiting machine learning techniques to automatize this step, by using standard and state-of-the-art border and shape recognition algorithms.

Optimal system design and LV grid reticulation

Once the load of the village is forecasted at the building level, the goal is to best design the low voltage grid to meet the demand while minimizing the electrification cost. The grid optimization process includes the following assets as inputs:

- LV grid infrastructure such as medium-to-low voltage transformers, LV cables, poles and customers connections;
- Individual solutions such as solar home systems (SHS);
- In case of microgrids with possible local power generation: solar PV panels, diesel generators and batteries (to store or withdraw electricity when needed).

This approach hence writes the problem as follows:

***Time horizon and granularity**:*

An hourly model is considered, with a typical representative week that is replicated to span a whole year. All costs are annualized (using local discount rates) and the optimization is carried out in perfect foresight. For the solar assets, the tool allows the user to tune the risk of the local solar irradiation to simulate for instance bad weather conditions.

Decision variables:
Decision variables are the degrees of freedom of the optimization problem that are tuned to minimize the total electrification cost of the village while satisfying the technical constraints for the proper functioning of the grid. The decision variables are:

- The PV, battery, generator sets and SHS capacity to install, their location and their operational functioning (hour by hour) to meet the load and the reserve requirements. These depend in particular on the solar irradiation at the village localization.
- The distribution grid: location of the cables, spots they need to connect, the location and number of overhead poles and the required number and sizes of transformers.
- How to connect the consumers: the model calculates for each customer individually whether it should be connected to the grid and where, or if the best solution on an economic perspective would be to provide them with SHS.
- The hourly operational flows of the network.

Objective function:
This is the function that one wants to minimize. The objective function is the total electrification cost including the investment, installation and operating costs of the generation and storage assets and the distribution network cables, transformers and poles. Load curtailment is possible in extreme situations, but it comes at a very expensive cost that is also part of the objective function.
It is worth mentioning that all decision variables are optimized simultaneously by the tool that has efficient ways to test all possible combinations in order to find the optimal one. As a consequence, it is not necessary to pre-specify to the tool the standard rules of thumb to arbitrage, for instance, between connecting a building to the LV grid or installing a SHS on its roof.

Constraints:
The tool finds the optimal decision variables that minimize the objective function, but it has to respect a certain number of constraints:

- The demand satisfaction constraint: each consumer must see its demand met by the grid at each hour.
- The technical constraints for the proper functioning of the PV panels, with the link to the local irradiation, and of the battery: maximum charging/discharging, energy to power ratios, etc. The reserve requirement constraints: at each timestep, the generation assets should be able to increase their generation by an amount that is specified by the user. These constraints make the grid robust to an unanticipated increase of the load and thus enhance the security of the system.
- The power flow constraints at each node of the grid.
- Some physical security constraints related to the minimum distance of the electric lines to the ground were implemented, by translating them into a maximum distance between two poles of the grid.
- Other additional constraints that could be requested by the user such as searching for an only 100% PV mix, centralizing the generation at only a pre-specified number of spots in the village that could be pre-specified or left to the model to be optimized.

Mathematical formulation and solving:
The obtained model is formulated as a complex optimization program, that has been re-written as a mixed-integer linear program (in particular, this required linearizing the optimal power flow equations). It is believed that the linearization is necessary if one wants to optimize an entire grid in a reasonable amount of time. Integer decision variables naturally appear in the model because many assets that are considered come in standard sizes. Therefore, the model ends up with situations where, for example, it has to decide at a node if it wants to put a PV panel or not, which induces 0 or 1 variables. The optimization is performed using a two-step heuristic. In the first step, the space is finely discretized and only the generation is optimally sized (PV, battery, generator sets and SHS). In the second step, the low voltage network reticulation is optimized. Since such a process can involve a huge number of variables, only a judiciously selected subset of possible grid lines is given to the optimization problem. The pre-selection of these lines is performed by running algorithms who can find minimum-spanning trees of the graph constituted by all the possible nodes of the network, including consumption nodes.
The model has been tackled using the commercially available CPLEX solver. For a typical village of 1,500 houses, among which 300 consumers were spotted, the whole load forecast and optimization phases last less than 15 minutes to run.

Outputs:
The tool provides the following outputs:

- The optimal sizing of the grid and its operational functioning in perfect foresight: PV, battery and generator sets capacity and location.
- The optimal grid design (reticulation) and operations.
- The total electrification cost of the village and the CAPEX/connection rate.

Future work:
The grid design step can be enhanced by taking into consideration more complex technical constraints related to the functioning of the grid. As an example, one could add some equations constraining where the cable could pass by (should they follow only the roads?). Moreover, the grid equipment overloading and voltage drops constraints are currently being integrated in a new version of the model. Once the grid is designed, it is foreseen that the tool runs a load flow analysis to determine the voltage at each node and the powers flowing in each branch. In this way, the grid equipment (medium-to-low voltage transformers and LV cables) loading and the voltage drops at the end of the LV feeders, which should not excess a user-defined maximum rate, will be checked. Another feature could be developed in the future to improve the performance of the tool, by optimizing the number, placement and total cost of several transformers (from a user-defined size range) over the villages/cities areas, taking the centres of mass of the loads into consideration. Cable sections could be optimized following the same approach, considering the benefits of line losses reduction compared to investments.
A stochastic optimization could also enhance the modelling: the investment would then be optimized by considering different scenarios of solar irradiation and energy demand.

USE CASE

An ongoing electrification project in Niger was the opportunity to test the performance of the developed model. In this country, more than 30,000 localities still do not have any access to electricity. One isolated village was selected to be studied in detail through this new model and compared with a traditional manual approach.

Kokoloko village
Kokoloko is a rural village in Niger located in Tillabery region, at 13deg14’57’’N 1deg00’57’’E. It has 1,278 inhabitants in 2018 and its population is expected to grow by 17% by 2035. The village has around 900 roofs among which 193 were spotted as potential consumers today.
The manual grid design resulted in an LV structuring network of 3.64 km and customer connections to this network of 3.86 km. The tracing of this network is shown on Figure 1. It consists in a structuring LV network (in black on the figure) along major paths between buildings of the village, accompanied by 193 short customer connections (in green on the figure) connecting this LV network to the different buildings. A medium-to-low voltage transformer is positioned at the geographical centre of the village (in yellow on the figure). The buildings that are not connected to the network (approximately 700) are considered subject to individual solutions such as SHS.

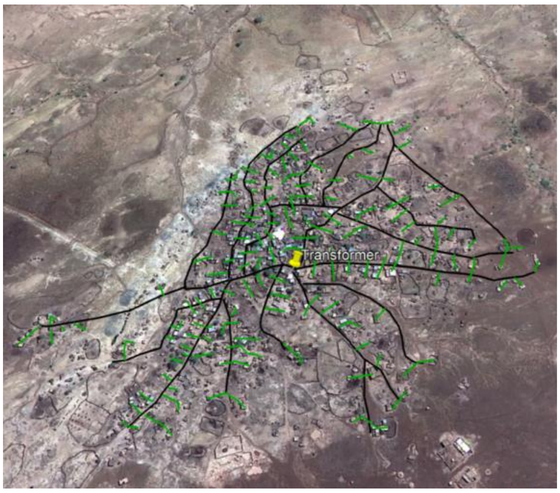

Figure 1: Aerial view of Kokoloko village with an LV network traced manually

Then, the methodology presented in this paper was used to design an optimal mini-grid with local power generation in the same village. One supply scenario was considered, with an optimal mix between PV and generator sets.
The demand forecast step led to the following features:

- Number of customers willing to get electricity through the network: 193. (Others will be supplied through SHS.)
- Village peak demand: 127 kW.
- Village average daily demand: 907 kWh/day.

A second scenario was run using the model and by artificially increasing the number of possible connections to 250 in order to analyse the impact of the demand on the CAPEX per connection rate.
The automatic and optimal sizing of the mini-grid led to the results presented in Table 1 for both scenarios:

	Scenario 1: 193 connections	**Scenario 2: 250 connections**
Optimal PV capacity	56 kWp	60 kWp
Optimal battery size	180 usable kWh	198 usable kWh
Optimal gensets size	69 kW	79 kW
Optimal cable length of LV structuring network	4.02 km	4.90 km
Optimal cable length of LV customer connections	3.20 km	4.10 km
Optimal poles number	107	127
Total electrification cost per connection	1,400 EUR	1,222 EUR

Table 1: Results of the mini-grid design

Figure 2 gives an overview of the optimal mini-grid to install in the two scenarios respectively.

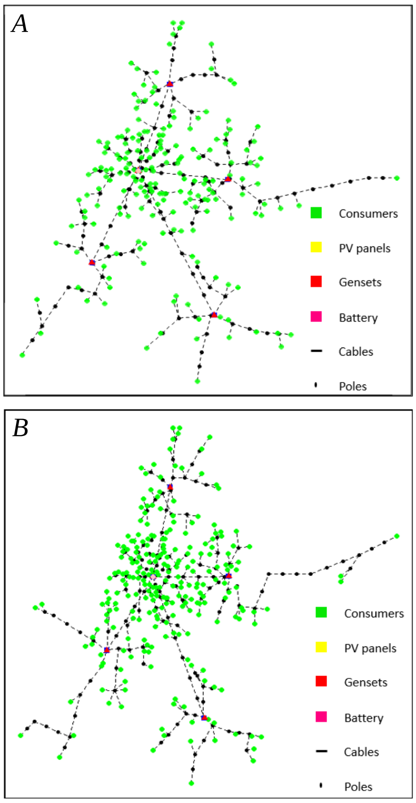

Figure 2: Optimal mini-grid in scenario 1 (A) & 2 (B)

While the LV structuring network of the manual approach is 10% shorter than in the proposed modelling, the customer connections are 17% longer, resulting in a 4% total length difference, which is shorter in the proposed model. The methodology not only led to an optimized LV network design: another important advantage in this modelling is the time earned to compute this network design. While the manual approach requested approximately one hour, the optimization tool ran in several minutes only. In case there is an important amount of unelectrified villages to study, like for instance in Niger, the reduction of efforts can be significant.
Finally, the model allows to estimate the electrification CAPEX per connection rate. An increase of the number of consumers from 193 to 250 will reduce this rate by 12%. This estimate is very useful for any LV-grid developer as it allows to better structure and prioritize the process of rural electrification beforehand. The tool allows to provide this estimate automatically in a few minutes.

Figure 3 reports on the evolution of the CAPEX per connection rate with respect to the number of power consumers in Kokoloko village. As the number of consumers grows, it becomes cheaper to connect the marginal consumer. In other terms, the more consumers in the village, the more efficient a grid connection will be, as compared to a solution involving SHS. If all houses can see their demand met by standard SHS, then crossing the curve of Figure 3 with the typical installation cost of SHS

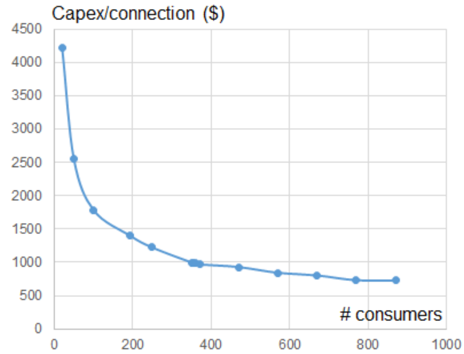

Fig 3: Evolution of the CAPEX per connection rate

will allow one to estimate the threshold of the number of consumers above which it becomes interesting to build a mini-grid.

CONCLUSION

The developed tool for the optimization of electrification solutions at LV scale is able to provide a load forecast at building level by mixing GIS and field information of the villages and to perform a techno-economical optimization of the low voltage grid and individual solutions such as SHS. This model appears to be of great interest for rural electrification planning, being able to determine quickly and effectively the best electrification solutions at low voltage scale within rural and unelectrified villages.

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