

## WHEN TO GO FOR MICROGRIDS? ANALYSIS OF THE MAIN DRIVERS IN ENERGY ACCESS CONTEXT

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### ABSTRACT

*Electricity access is currently limited in today's developing countries. While efforts can be observed worldwide to move to a universal access, the question lies to determine what the best way is to ensure power supply to predefined localities: through connection to the existing grid, or via microgrids or smaller individual solutions like solar home systems or solar lanterns. Tractebel has developed a new GIS-based tool to make this arbitrage and determine the costs of electricity supply for each locality, i.e. for the end customers. The tool also designs Medium Voltage network expansions (from renewable energy sources as from existing grids) at the scale of a complete region while respecting load flow constraints. The proposed paper presents this new simulation tool aiming at identifying where microgrids make sense compared with grid expansion solutions, and how those microgrids must be designed geographically.*

### ENERGY ACCESS TODAY

Electricity access in developing countries is currently limited: in 2014, about 15% of the population worldwide (1 billion people) did not have access to electricity [1]. Several factors are responsible for this limited access. Among others, local utilities generally face strong budget and/or geophysical access constraints while connecting customers in widely spread rural areas with low population densities or poor financial health.

Fortunately, electricity access is nowadays one of the top governments priorities and is supported by international donors, especially through the Sustainable Energy for All Global Initiative that seeks access to energy for all by 2030 [2]. Thereby, positive factors exist to allow a rapid increase of the electricity access rate. In particular, numerous private actors complement the efforts of the national utilities and microgrids become more and more economically relevant for rural electrification. Furthermore, in most of developing countries, large amount of renewable resources (mini-hydro, sun, biomass, wind) are available, enabling rural communities to be supplied locally. This has been reinforced in the recent years by the decline of the costs of technologies specific to rural electrification (namely solar photovoltaic panels with batteries).

### MICROGRIDS RELEVANCE COMPARED WITH GRID EXPANSION

#### Advantages of each solution

In the present context, microgrids development appears to be an interesting option to electrify populations in rural areas either isolated or far from existing electricity grids. However, their interest must be guaranteed compared with grid expansion solutions that present the following advantages:

- (i) The power level that users can contract is generally less limited via grid expansion than with microgrids.
- (ii) Grid expansion generally allows supplying electricity with both single and three-phase connections, while microgrids frequently supply customers with only single-phase electricity. Microgrids thus require additional systems that are expensive to run three-phase motors.

Knowing that microgrids can provide better network reliability (i.e. better quality of service) than grid expansion, one must ensure finding the most appropriate solution to all households needs and ability to pay. Energy access objectives do indeed not necessarily imply a common level of services for all: people have different needs, both in terms of quantity of energy requested (for engines versus for lighting) and in quality of service required (few versus 24 hours a day).

#### Best sites identification

Whether investing in microgrids or in expansions of a main grid, a question is to determine what villages must be supplied in priority. The investors' perspective must for that be identified as it can differ from the one of electrification agencies, the latter aiming at electrifying a maximum of people for the lowest cost, maximizing thereby their socio-economic impact for given budgets.

For microgrids, the cost of the solution in one particular village depends mostly on the chosen generation units and on the size of its electric loads. It can thus be assessed independently from other localities in the vicinity. For larger microgrids supplying several villages at a time, the cost of the solution must however be assessed considering simultaneously all the localities around the site retained for the generation source.

To a greater extent, for grid expansion, one must look at the entire region to determine how to develop the network. Important costs variations can indeed be

observed with the local conditions, such as: (i) the distance between villages and the network, (ii) the number and density of villages in the vicinity likely to share the grid expansion costs, or (iii) geographical constraints (lakes, rivers, mountains, forests, etc.).

To assess properly the cost of a grid expansion to a predefined locality, a specific tool integrating geographical data is therefore required to serve as a basis for arbitrage with the microgrid option. The goal of such a tool is to determine the least-cost electrification solution (grid expansion or microgrid) for each single locality in the studied area.

## RURAL ELECTRIFICATION TOOLS

### Existing Tools

At present, several initiatives have been emerging worldwide (for instance by SE4ALL, the African Development Bank or the World Bank) to provide planning tools for electrification (i.e. load forecast, site selection, minigrids sizing, financial analysis, etc.). Among them, OnSSET [3], GEOSIM [4], Network Planner [5], LAPER [6] and Strathclyde University's tool [7] appear specific to the arbitrage between the expansion of a main grid and other off-grid solutions (microgrids or individual solar home systems). Those tools present however some limitations regarding the computation of the main grid solution as they mainly focus on the off-grid solutions. Limits concern (i) the meshing size of the country/region to analyse when aggregating data, (ii) the need for grid constraints integration (assessment of voltages and power in the network), (iii) the precision on the distances computed to the grid or between localities (presence of obstacles or existing infrastructure), and (iv) the maturity status of the tool (not yet mature or outdated).

### Presented Tool

A new tool has been developed by Tractebel to analyse the arbitrage between the on-grid and the off-grid electrification solutions considering both load flow constraints and geographical data. Distances are there computed taking into account impenetrable zones (lakes, protected forests), zones that should preferably be avoided (frequently flooded areas, agricultural fields, big terrain slopes) and preferred zones (existing roads or railways).

### Goals of the tool

The features of the tool are the following:

- (i) Determining, at the scale of a region or country, what villages must optimally be supplied by network expansion and what others through microgrids. Expected results are GIS maps showing the optimal solution for each village of the region or country.
- (ii) Designing the optimum network architecture of microgrids to connect several villages located around a unique (renewable) energy source at lowest cost.

### Algorithm

The tool relies on levelized costs of electricity (LCOE) computed for both the grid expansion (per branch) and the microgrid cases. LCOE is defined in equation (1).

$$LCOE = \frac{\sum_{t=1}^n \frac{C_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \quad (1)$$

$C_t$  and  $E_t$  are the cost (CAPEX and OPEX) and electricity consumed at year  $t$  by the localities to electrify.  $r$  and  $n$  are the discount rate and the expected lifetime of the system. For the grid expansion case, localities costs and electricity are aggregated by new network branch.

The grid expansion LCOE is obtained considering the whole power system chain: it contains the costs of generation, reinforcement of the main grid if necessary and expansion of the grid to the entry of the MV/LV transformers of each locality.

The tool minimizes the total cost of electrification for the area of interest. After an initialisation of the GIS database, the tool clusters the villages to connect and defines the main developments of the network (backbone). This clustering process is achieved based on a hierarchical clustering method that presents two advantages: being reproducible (giving the same results for different trials on the same inputs) and not needing a predefinition of the number of clusters in the end solution. After the clustering, the shortest path problem is solved via Dijkstra's label algorithm [8]: the total distance of the localities to the main grid is minimized via several new network branches.

### Inputs and outputs

The inputs of the tool concern the costs, locations and technical data necessary for the determination of the optimal network expansion and the computation of the resulting LCOEs. They contain: (i) existing and planned generation facilities data providing the average marginal cost of production of electricity in the region, (ii) the network topology and its technical parameters (loads, impedances, voltages, etc.), (iii) costs and technical data on equipment for the expansion of the main grid or the development of microgrids, and (iv) the villages to connect with their expected loads, locations and required levels of services.

Regarding the outputs, the tool provides: (i) detailed lists of the villages to be connected to the national network and of villages to supply with new microgrids, with the respective cost of connection of each village, (ii) the optimal routing of the grid expansions to build to connect the localities from the main grid, with a prioritisation order of those lines or cables, and (iii) AC load flows and losses in each new branch of the network with voltages at each node of the system.

## APPLICATIONS

Two applications for which the developed tool can be helpful are emphasized in this paper: (i) a design of an MV distribution network connecting several villages to one common generation source, and (ii) the determination of the villages to connect preferably to an existing grid or to supply via microgrids.

### MV microgrid design from one power source: What is the optimal network architecture of a microgrid supplying several villages?

The first application concerns the design of an isolated MV network supplying villages from one unique (renewable) energy source. Such a case can for instance be found in islands or in regions located far from existing national distribution grids.

Starting from a set of villages identified with their respective coordinates, the load of each village is forecasted. Then, knowing the local renewable potential (i.e. the power the renewable energy source can deliver to the microgrid), the tool presents the collected data via a GIS map showing both the geographical location and the size of each village to electrify from the power source (Figure 1).

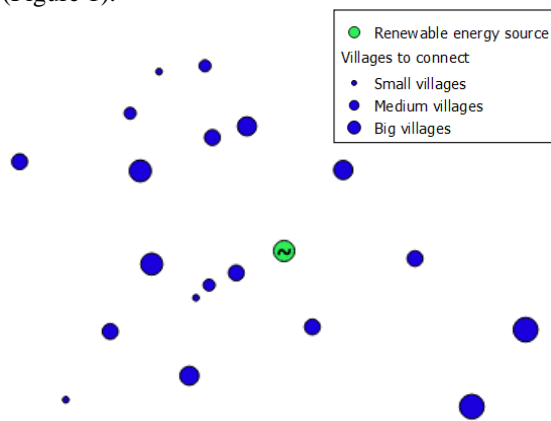


Figure 1: MV microgrid design from one unique generation source – Initial set of villages

Based on that, the tool minimizes the total cost of the network to build: it groups first the villages by clusters and identifies the centres of mass of those clusters (with loads as weights). Following that, it connects the centres of mass with the minimum cumulated length for the entire network. By reducing progressively the size of the clusters, the tool defines an optimal MV architecture for the microgrid.

Once the architecture of the microgrid is set, the tool runs a load flow analysis to determine the voltage at each node and the powers flowing in each branch (Figure 2). In case one part of the network does not meet the requirements, it is rejected from the solution before the tool tries to reconnect it via another path.

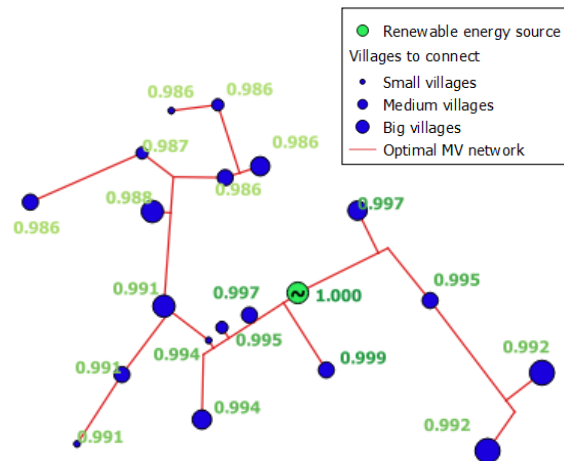


Figure 2: MV microgrid design from on unique generation source – Final microgrid architecture; numbers indicate the voltage (in per unit) at each entry of village

The resulting solution is provided together with the cost of each new MV branch to build and with the LCOEs (EUR/kWh) for all supplied villages.

### Arbitrage between grid and off-grid supply: Where microgrids make sense in the vicinity of the national network?

A second application consists in building maps of a region or country with the existing electricity networks and the surrounding villages, with the best supply option (grid expansion or microgrid) for every village separately. This way, the tool can serve as a motivation to convince authorities and investors that some localities will for instance not be connected to the national grid in the coming years, securing thereby a potential microgrid business case related to those localities.

Using the algorithm described above, the tool defines the minimum-cost network expansions that allow new localities to be connected to the main grid while respecting load flow constraints. Then, by comparing the costs of the different electrification solutions (grid expansion versus microgrid), the tool specifies what option is the most techno-economic for each village.

The Figure 3 illustrates this application for a small network surrounded by 68 localities to electrify. The presented map summarizes the best supply option for every locality individually based on its colours: blue for those to be connected from the existing grid, orange for those to be supplied via microgrids. The results show that localities close to the existing network are naturally recommended to be electrified by new branches from the existing grid as the short distance makes cheaper the grid-solution than the microgrid one.

For other localities further from the network, however, it appears interesting to connect them to the main grid only if individual loads are sufficient to compensate the cost of network expansion or in case the additional branches can be shared between them (i.e. if the localities are close enough to one another).

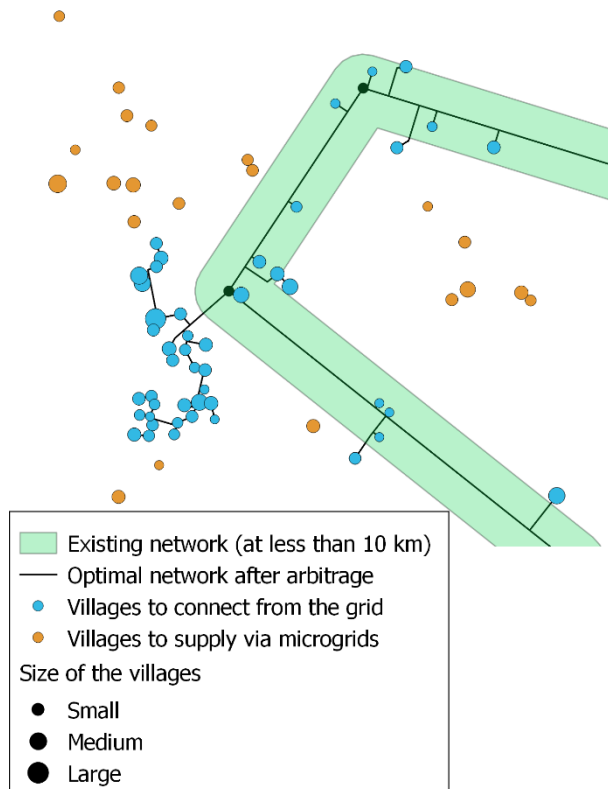


Figure 3: Arbitrage between on-grid and off-grid supply of villages around an existing MV network

## CONCLUSION

Tractebel has developed a new tool to analyse where microgrids make sense compared with grid expansion solutions, and what MV architecture those microgrids must optimally follow. The tool determines how to connect localities from an existing network or from a common generation source. This can be used to both design MV networks among microgrids and define expansion plans at the scale of a region or country. For each assessed locality, the optimal supply option is given, as well as the minimum cost of electricity that must be paid by the customers to make the business plans profitable for the investors (without subsidies).

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