Renewable-based isolated microgrids instead of replacing existing MV lines supplying rural areas

Alejandro López Vernet
alejandro.lopez.vernet@gmail.com
Instituto Superior Técnico, Universidade de Lisboa, Portugal

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***Abstract* — Spanish MV lines supplying rural areas are approaching the end of their lifetime. A replacement of these assets will soon be needed. However, those areas' low population densities make the distribution system very long, leading to a very high investment per customer supplied. This paper explores the possibility of using renewable-based isolated microgrids, with PV and Li-ion, as a replacement of MV lines in those areas. A techno-economic study is performed to find the threshold distance and load from which the microgrid is a better option. As a first step, the behavior during an entire year of different communities is simulated using a load forecast model. This model's output is used together with techno-economic parameters of solar PV and Li-ion technologies to optimize the microgrid's asset size, using Prosumer as the optimization software. Ultimately, the project's total costs of the microgrid are obtained. Later, the project cost of building the MV lines is computed and compared to those of the microgrids to obtain the threshold distances and loads that define the optimal project to consider. It is concluded that the approximate distance of MV line that can be built per each customer is 187 m. For projects where the length per customer is greater than that, it is preferable to build a microgrid from the economic point of view. At the end of the paper, sensitivity studies are performed on the business case's main uncertainties. Different options are considered to reduce the microgrid costs and make the business case even more favorable.**

***Keywords* — Microgrid, MV line, Load Forecast Model, Renewable system, Rural, Isolated**

I. INTRODUCTION

In Spain, the cities' electrification began at the end of the 19th century and continued during the 20th century. The residential electrification had very different paces in urban and rural areas due to the electric system's low rentability in rural environments, where long lines are required to supply a few customers. In 1972, the 3rd National Development Plan [1] was approved. According to the document, in 1972, 230 thousand Spanish people still did not have electricity. When this paper is being written (2020), the last distribution assets built to reach the most isolated places in Spain have been in use for 40-50 years and they are at the end of their regulatory life [2].

In addition to this problem, the migration of the population from a rural environment to cities worsens the outlook. During the last 50 years, the rural population decrease has been dramatic, around 40% on average, with the most affected areas exceeding a 50% population loss [3]. These extremely low densities lead to very long MV lines, making the cost per customer very expensive.

In this paper, the possibility of implementing an isolated microgrid instead of replacing the medium voltage (MV) line in remote rural areas in Spain is explored. Some of the beneficial effects that this change would have are a reduction of the costs per customer of the distribution system in rural areas, an increase in system efficiency due to the reduction of electricity transportation losses and, in the case of renewable microgrids, they can also increase the penetration of renewable energies in the system. This is in line with the Paris agreement [4], where Spain committed to reducing its greenhouse emissions by 40% in 2030 (compared to 1990).

The type of microgrid that will be simulated will be completely renewable-based. Taking advantage of Spain's great solar potential, the only generating asset considered will be solar photovoltaic modules (PV). For energy storage, a Lithium-ion battery is going to be used.

The main question that wants to be answered in this paper is:

Is it economically feasible to supply the customers in these villages with a microgrid instead of a renovation of the distribution network? What are the necessary conditions to have a positive business case?

The structure of this paper is as follows. In Chapter II, the literature review can be found. In Chapter III, the methodology followed to run the simulations is explained. Furthermore, an explanation of the load forecast model and all the changes and adaptations can be found. In Chapter IV, the results of the simulations are presented and discussed. Afterward, the total discounted costs of the microgrid and MV business cases are computed. The comparison of both cases is also given. In Chapter V, the conclusions of the study can be read.

II. LITERATURE REVIEW

After an in-depth review of recent articles, it can be seen how most of the studies related to stand-alone microgrids take place in developing countries to electrify villages where electricity was not available before. This fact has significant importance for two details. Firstly, in developing countries, load growth is always expected, and in developed countries' rural areas is usually the opposite case. Secondly, the economics are very different, due to the accuracy of the asset prices and the lower risk in developed countries.

For example, Masrur et al. [5] studied the development of an isolated grid for 8000 people in Bangladesh, following a bottom-up approach for the load-simulation. They concluded that a combination of PV, wind, diesel-generator, and battery was 30% cheaper than a diesel-only system. Vendoti et al. [6] and Kaur et al. [7] studied an off-grid solution for 400-household and 236-household villages in India. They did surveys to estimate the load. The first concluded that the best system had a combination of wind, solar PV, biogas, biomass, fuel cell, and battery, achieving an LCOE of 0.214 $/kWh. The second obtained a PV and biomass system as an optimal solution, being the LCOE for the isolated case 0.1568 $/kWh and for the grid-connected case 0.0735 $/kWh.

Another trend seen in the previous papers is that the case studies used to be about relatively big communities, with more than 100 people living in them. The load profile on large communities during the year can be easily estimated because of the averaging effect of big groups of people. Analyzing the studies related to very small communities, it can be concluded that they tend to be simpler, having as an optimal solution in most cases a combination of PV and battery.

For example, Akinyele and Rayudu [8] studied implementing a solar microgrid in Nigeria for a community with 20 houses, based on surveys on their consumption habits. They concluded that a PV system between 55 and 82 kW would provide electricity 97% of the time, with total costs below 500k€. Murty and Kumar [9], considered several different technologies for a stand-alone system in a 30-house community in India. They found that the optimum system was PV and battery. However, the LCOE price obtained was higher than the grid one.

Some studies have been found in developed countries. However, to find analysis made on stand-alone systems was challenging. The only cases where stand-alone microgrids are considered as a feasible alternative is in the islands.

For example, Thomas et al. [10] studied the implementation of a renewable-based microgrid in a Greek island with 300 inhabitants. They obtained the load directly from measurements. They concluded that a system with wind, battery, and diesel generators would have the lowest costs (1.8 million€), but a high carbon footprint. Adding PV to the previous configuration would lower the footprint but increase the price to (2.25 million€). A complete renewable system with PV and Wind would have very high capital costs (6.5 million€). Hafez and Bhattacharya [11] studied how to supply a 500-house community in Canada. They found that the cheapest off-grid option would be a hybrid system, followed by a renewable-based system and a diesel-only system as the last option. However, none of those options was cheaper than the grid connection.

III. METHODOLOGY

In this chapter, an introductory explanation of Prosumer and its applications' scope will be done. Afterward, the inputs required to run the simulations and characterize the PV-based microgrid will be given. At the end of the chapter, an explanation of the load forecast can be found.

A. *Optimization software: Prosumer*

Prosumer is an advanced simulation and optimization tool developed by Tractebel [12], that aims at defining strategic planning for multifluid energy investments at the territory level. It designs the optimal configuration minimizing the total cost of ownership of the system. Its ultimate goal is to arrive at a concise and clear investment decision. Prosumer determines the optimal size of the different assets to fill energy needs. The tool integrates physical modeling of the different equipment, including the technical constraints and the associated costs (both investment and operation). These additional constraints are integrated into a mathematical model that is solved using a state-of-the-art commercial solver.

B. *Simulations conditions*

For this paper, the inputs will be adapted to a rural, isolated microgrid case located in Spain. In the following paragraphs, the inputs used for the simulation and their sources will be given. In Table 1, the main inputs for Prosumer can be seen, together with the sources.

TABLE 1
MAIN PROSUMER INPUTS AND ITS SOURCES

Prosumer Input	Source	Value
WACC	Renewable power generation costs in 2018, IRENA [13]	7.5%
PV	Production Profile: Photovoltaic geographical information system (PVGIS), European Commission [14] Costs: Renewable power generation costs in 2018, IRENA [13]	Build cost: 1000 €/kW O&M cost: 17€/kW
Li-ion Battery	Laborelec	Build cost power: 300 €/kW Build cost capacity: 300 €/kWh O&M cost: 2% of CAPEX
Load	CREST model (section III.C)	

The project duration will be set to 40 years because it is the average lifetime of some critical assets considered, such as the MV line [15]. The optimization will only be done once at the beginning of the project, and no learning curve will be applied to the prices.

The only generating asset considered for the microgrid was solar PV. This decision was made due to the high potential of this technology in Spain and its maturity and proven feasibility in numerous renewable projects.

Li-ion technology was selected as the storage. The fact that Li-ion is a much more mature technology makes the difference. The offer in the market and certainty on prices will be much higher. As a consequence, the projects that include them are easier to finance. For the inputs needed in Prosumer, Laborelec values were taken [16], based on the values for current projects currently under development. The technical parameters can be seen in Table 2. The maximum Depth-of-Discharge (DoD) indicates the maximum percentage of the battery energy capacity that can be discharged. The energy-to-power ratio (E/P) is the time (h) that the battery can be in operation, supplying energy at the rated power.

TABLE 2
TECHNICAL PARAMETERS LI-ION BATTERY

Parameter	Value
Round-Trip Efficiency	85%
Max DoD	0.8
Capacity Loss [kWh/y]	0.02
E/P range [h]	0.25-10
Dissipation Rate [h^{-1}]	4e-5

C. Load Forecast Model

The hour-resolution demand during all the year is one of the key inputs. An unrealistic power demand profile could easily lead to a misleading final result. It is also the most complex input to obtain due to the lack of data on the internet of small rural communities.

The goal is to input the demand of small communities (from 1 to 10 houses) in a rural environment. The loads available on the internet would not be adapted to such a case because they are usually averaged through many houses and not adapted to rural locations' behavior.

A simulation of the demand profile was considered the best solution in terms of realism and customizability. Therefore, a probabilistic demand model created by scientists from Loughborough University [17] was found and adapted to the needs of this study to forecast the load of the hypothetic community. The original model, created with Visual Basic by Ian Richardson et al., is publicly available to download [18].

The model uses the appliance as the base building block, creating the final dwelling demand profile from the sum of all the appliances. Using a pseudo-randomly generated occupancy profile and daily activity profiles generated from surveys in the UK, the switch on events of the different appliances is defined.

This model allows to simulate small rural communities, because it is highly customizable and can simulate demand profiles of single households in a realistic way. However, some disadvantages remained that made them useless for this study. It can only obtain the profile of one day, it is based on UK behavioral data, and it does not include some important appliances, like air conditioning. The code and the part of the data were modified to overcome the model limitations for its application in this study.

First of all, the code was adapted to obtain the data in the format needed to input it in Prosumer, an hour-resolution profile during the 365 days of the year. To obtain the yearly load, it was modified to run 365 times in a row and store all the days simulated. Some considerations had to be made when doing these modifications, like the differentiation between weekday and weekend.

Another important thing to change was the sun irradiation profile used by the lighting model. The same irradiation profile in the South of Spain used as an input for PV was taken from PVGIS [14]. An interpolation was done using to change the data to minute-resolution to use it as an input for the load forecast model.

Once the whole model's output result was obtained, an integration hour by hour was made.

The second topic to address was modifying the model's database to adapt it to the consumers' behavior in Spain. The average electricity consumption per household was extracted from the TSO and was set to 3270 kWh/y [19]. Presumably, this value would be lower in rural areas because electric heating and cooking appliances are not as common as in the rest of the country.

The average consumption of each appliance and the ownership data were extracted from two official documents (Spahousec I and II [20], [21]).

As in the UK cooling systems are not common, the original model was not equipped with air conditioning. According to a study from the National Institute of Statistics INE [22], around 35% of Spanish households are equipped with this appliance, reaching values over 70% in some cities. Therefore, the code was modified to include this appliance.

The space heating and cooling coefficients were also adapted to the weather conditions. Due to the climate difference, the monthly probability factors of using those appliances were changed to match the Spanish case [21].

Activity profiles were not possible to customize for Spain due to the lack of high-resolution Time Use Surveys. However, activity profiles for the UK were modified using the author's personal experience. The cooking activity profile was delayed 2 hours from the original one, and all the rest of the activities were delayed 1 hour.

The strategy for creating the final loads was to run the simulation ten different times, making ten yearly loads for ten individual households. For the one house case, one of the loads was selected. For the two-house case, the previous one-house load was picked and summed up with another of the individual loads obtained. The process continued until ten yearly loads were obtained, representing communities from one to ten households. Following this method, the simulation results' consistency can be guaranteed because to generate the load with n+1 house, the n case is used as a base. Therefore, the effect of adding one new house to the community can be observed.

IV. SIMULATION RESULTS AND ANALYSIS

In this chapter, the results of the simulations done with Prosumer will be exposed and discussed. Afterward, the microgrid project's total discounted cost will be computed, adding to the simulation results some extra costs not considered by Prosumer. Then, some research will be made on the costs of building, operating, and maintaining an MV line in Spanish territory. Once the total costs of the two possibilities are obtained, a comparison of the two options will be made.

A. Simulation Results

Ten base cases were done, with the only difference between them being the load given as an input, representing communities from one to ten houses.

The battery energy and power were found to be proportional to the number of houses in the community. Prosumer was installing approximately 3 kW extra of battery power and 25 kWh of energy capacity for each extra house.

The amount of PV installed is also directly proportional to the number of houses. Figure 1 shows the size of the PV system for the ten cases evaluated. As can be seen, for every added house, 6 kW extra are included in the system. The PV is oversized by the software to supply the community in the days with less irradiation in the year.

The discounted cost calculation for the project was done by Prosumer. The price of adding an extra house to the simulation is constant and has an approximate value of 25 k€. This consistent price difference allows to easily extrapolate the results for bigger communities.

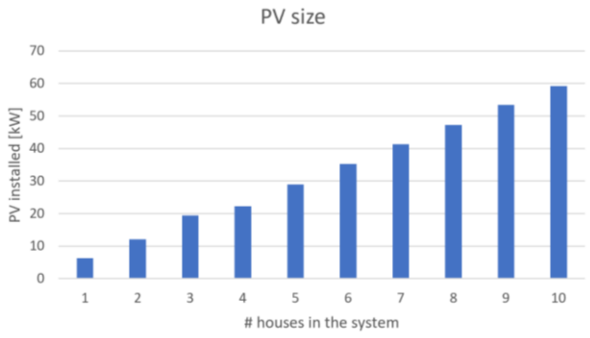

Fig. 1. Size of the PV installation for the ten cases

B. Total Microgrids Costs

The total discounted cost of the generating and storage assets are only a part of the full costs that involve the construction of a microgrid system. Some extra costs must also be considered.

Taking as a reference a cost study made by NREL on 80 microgrid projects in the US [23], it can be concluded that the total price changes significantly depending on the market segment where the microgrid belongs. The document also goes into more detail in the breakdown of the costs of community microgrids. Based on the study, the control system represents 3% of the costs, and soft costs and additional infrastructure 9% of the costs. These extra costs must be included in the microgrid's total costs.

The control system is a fundamental part of the microgrid. It controls the electricity flow in the microgrid and the charging and discharging of the battery. Considering the investment on the controller as a 3% of the initial investment, as suggested by NREL, and dividing the controller's investment cost by the microgrid’s power (PV+battery), the average price for this equipment is obtained: 60 €/kW.

The soft costs include engineering, construction, commissioning, and regulatory costs. The value for the community microgrid, of 9%, was taken. Following the same procedure as before a value of 181 €/kW was obtained.

Additional electric infrastructure costs include all the expenses on tangible assets, excluding generation equipment (cables, poles, circuit breakers, etc.). According to the NREL study [23], for community microgrids, these assets' value is approximately the same as the soft costs; thus, 181 €/kW will be considered.

With all the extra costs computed, an estimation of the total discounted costs for the ten cases can be done. Figure 2 shows the total cost disaggregated by categories.

$$\textit{Total discounted cost} = \textit{Storage} + \textit{PV} + \textit{Soft costs} + \textit{Add.infrastructure} + \textit{Control sys.}$$

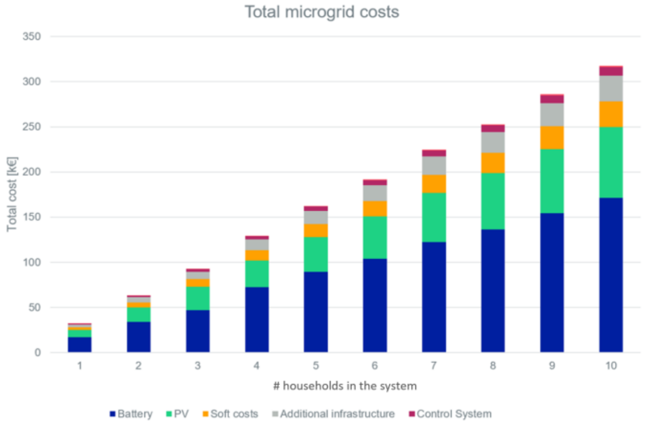

Fig. 2. Total discounted microgrid costs disaggregated by category

The number of dwellings is directly proportional to the project's total cost, being around 32 k€ the price for every added house in the system.

The total discounted costs per MW can be obtained by dividing each of the cases’ costs by its power (PV+battery). If this is done for the ten cases, an average of 3.6 million €/MW is obtained.

C. MV line cost

In this section, the MV line cost will be computed. It is crucial to notice that, unlike microgrid costs, MV line cost will depend on the number of kilometers to be built.

Spanish regulator periodically publishes the reference prices for the distribution assets to avoid frauds and over costs from the distributors. This document has been used to determine the MV line costs [24]. Only the cost of the MV lines and the MV/LV transformer will be considered. The costs of the electrical protection equipment will be omitted.

The project's cost for the 40 years lifetime can be computed. Considering a 7.5% discount rate, a total discounted cost of 52960 €/km was obtained for the MV line, plus 17113€ of the transformer.

The remaining factor is the length of the MV line, which will be one of the variables used to make the comparison. The total discounted costs of the MV line project will be computed multiplying the discounted costs of the MV line per kilometer by the required length plus the discounted cost of the transformer.

D. Microgrid vs. MV lines

This section aims to identify the threshold distances and load that makes the microgrid business case favorable compared to the MV line reconstruction.

On the first hand, the distance from the community to the primary grid is crucial because the costs of reconstructing the MV lines depend primarily on this value. On the other hand, the amount of energy needed per year is also important. It has been shown how the costs of building the microgrids depend proportionally on the number of houses of the system (i.e., the number of people in the community).

In the previous sections, the computation of the total discounted costs for both projects has been explained. Equaling these costs, the threshold distance from which it will be more favorable to build a microgrid can be obtained. It will be computed subtracting the discounted costs of the microgrid and the transformer, and dividing the result by the discounted of the MV line per kilometer.

Figure 3 shows the threshold distances that make the microgrid case economically better than replacing the MV line.

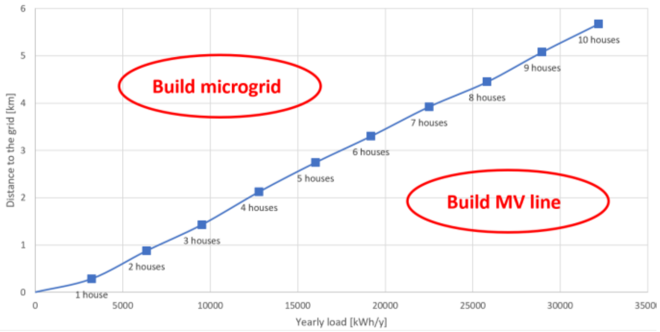

Fig. 3. Threshold distances of the business cases

For a single dwelling (approx. 3 people) that is more than 280m away from the main grid, it would be favorable to build a microgrid instead of an MV line. As the number of houses (and people) increases, the distance goes to higher values, up to 5.6 km for the ten-house case (30 people).

As a rule of thumb, the number of feasible meters to build per each customer will be given by the line's slope. This slope is approximately 187 m/customer, which means that for every customer to supply, up to 187 meters of MV line can be built.

E. Real case

Two parameters can serve us as guidelines to find areas with optimal conditions to build microgrids. These are population density and population dispersion. A Spanish village's real case is shown in this section to clarify microgrids' potential and calculate the expected savings.

The village selected for the case was Ocentejo, located inside a low-density area. Ocentejo population evolution is very representative of the demographic problems present in this area. According to the National Statistics Institute [25], in the year 1900, it had 255 inhabitants. However, nowadays, only 18 people are living there.

Mountains surround the village, and it is only reachable through a curvy road. The closest village is Sacecorbo. The distance between both villages by car is 9.3 km, which can be considered the MV line's length.

Looking at the base case results obtained, for an 18 people community (around six houses in terms of energy used per year), the threshold distance is 3.3 km. In this case, the real distance is almost three times the threshold distance.

The estimated price for six houses microgrid was: 191730€. If the equation to compute the MV line costs is used, setting 9.3 km as the distance to the main grid, the costs of the distribution line can be obtained: 509640€. If the two values are subtracted, a saving potential of 317910€ is obtained.

Building an MV line to those places would be a waste of resources. Moreover, the main microgrid assets can be easily reused in other projects around the country if a village becomes deserted.

V. CONCLUSIONS

In this paper, the feasibility of installing an isolated renewable-based microgrid with solar PV and Li-ion has been compared against the construction of an MV line for remote rural communities in Spain.

A load forecast model for individual dwellings was developed. It allowed the pseudo-random simulation of small rural communities' yearly demand profiles, with a high degree of customization. The model could be successfully adapted to Spanish rural areas' behavior, giving precious input for the simulations that could not have been obtained otherwise. This model can be used in the future to simulate small communities whose appliance configuration and behaviors are known.

Afterward, the yearly demand was used together with other economic and technical inputs to optimize the PV modules' capacity and the battery. This optimization was done with Prosumer, an advanced simulation and optimization tool developed by Tractebel Advisory & Advanced Analytic. The final results showed that the approximate increase rate for each extra house included in the simulation was +6 kW/house for solar PV, together with +3 kW/house and +25 kWh/house for the battery.

However, more costs had to be considered to have a realistic cost estimation. These costs included the soft costs, the control system's cost, electrical equipment, and land cost. All these were estimated based on existing microgrid projects. The rate of increase in the costs found was +32 k€/house. In other words, the total discounted cost is 3.6 million€/MW, a value that is in line with other similar microgrid projects registered in the US.

The total discounted costs of both cases were equalized to compare the microgrid with the MV line. As a result, a formula for the threshold distance from which the microgrid business case is more favorable was derived. Averaging the results for the ten different communities simulated, it can be concluded that the maximum MV line length that can be built per customer is 187 m. If the length per customer is greater than that, a microgrid should be considered instead, from an economic perspective.

To finish the paper, a preliminary analysis of the savings on a real case was computed. The areas with the most potential for microgrids were identified and explored. As an example, the village of Ocentejo was identified. The savings were found to be well over 300k€, representing the huge saving potential.

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