Optimal Planning of Micro-Grids Powered by Renewables

Guilherme Castro
Instituto Superior Técnico, University of Lisbon
guiccastro8@gmail.com

Abstract— **In the past, the electricity cycle was based exclusively on the use of large power plants, which then transmitted the power through high voltage lines over long distances and then distributed it to consumers at the appropriate voltage for consumption. In recent years, electric power systems have gone through a transition phase, integrating a new concept of dispersed small-scale power generation using renewable resources or efficient generation technologies directly connected to medium (MV) or low voltage (LV) networks. In order to be able to integrate these ideas, the concept of micro-grid (MG) arises: a MG is a MV or LV network capable of operating in interconnection with the local distribution network, or in isolated mode (disconnected from the distribution network), powered by local generators. The topic of this paper is focused on the MG and, in particular, on the problem of operation and integration in electric energy networks and related economic issues. The energy consumption in a MG may have different costs, depending on the type of local generation, the type of interconnection to the distribution network or even the size of the MG. Therefore, it is relevant to perform economic studies in order to identify the most economically viable solutions in relation to the feeding of the loads of a MG. In order to make a contribution to the problem assessment, several cases of MGs operating in interconnected and/or isolated mode are analysed, which are differentiated by the size of the MG loads, the local generator technology and the type of network interconnection line. For each case, a quantitative evaluation of some parameters related to these variables is made in order to identify the most economically advantageous solution. The economic indicator used is the Levelized Cost of Energy (LCOE). This indicator is usually used to calculate the cost of producing electricity in a power plant, but, in this paper, this concept is extended to the cost of energy transmission in a power line, integrating the fixed cost, variable cost and losses cost.**

Index Terms—**Micro-grid; Distributed Production; Local Generation; Distribution Networks; Renewable Energy; Network Planning; Economic Analysis.**

I. INTRODUCTION

In the past, Electric Power Systems were based on large power plants that use fossil fuels (mainly natural gas and coal) to produce energy. The electric energy produced was transmitted through very high voltage power lines at long distances, and finally distributed to the consumers at a voltage level suitable for consumption. The power flow was only from the power stations to the consumers.

Over the last years, this paradigm has changed. A new concept of decentralized production based on low-power sources powered by renewable resources or more efficient generation technologies has become a part of the generation portfolio. Passive systems with unidirectional energy flow from the high voltages to the low voltages tend to become active networks with bidirectional energy flow [1].

This change has been driven by developments in low-power generation systems that, together with environmental concerns and the support from energy policies, have enabled the growth of Distributed Production (DP), mainly using renewable energies, directly connected in the Low Voltage (LV) or Medium Voltage (MV) networks.

These factors led to a power system change, or, better saying, a power system evolution that resulted in the emergence of a new concept: a micro-grid (MG), i.e. a local distribution network in LV that associates DP sources (photovoltaic (PV) panels, fuel cells, etc.), storage devices (batteries or capacitor banks), loads (consumers) and a control structure responsible for the management and control of the MG [2].

One of the distinguishing features of MGs is their ability to operate, either interconnected with the local MV or LV distribution network, or isolated from the network. In this way, the reliability of the MG is increased, since there are two ways of feeding the loads: either the local network or the internal sources of micro generation.

Given the high integration of DP, a MG can provide a more efficient power distribution system. For example, the power losses in the lines are reduced, since the electrical distance between production and consumption is reduced. Reducing losses and increasing energy efficiency can lead to significant economic gains. In this way, the sustainability of the traditional centralized generation system has been questioned, because the construction and expansion of new conventional power stations would require a restructuring and investment in the existing grid. The MGs, despite not being able to compete in terms of production capacity with existing conventional power plants, can be competitive, following the development of the power system, and making electricity markets less volatile and at more affordable prices.

The emergence of DP connected to the LV or MV network has the potential to reduce the cost of energy billing for consumers in the long term and to provide electricity free of pollution associated with fossil fuels. However, traditional power systems also offer smaller risks and increased security for consumers and are heavily deployed in today's society [3].

Everything points to the fact that the future of the power systems is intrinsically linked to the development of the MG concept, which makes this topic very attractive to be studied. The possibility of identifying solutions for MG expansion, in particular through an economic analysis of its operation, either in isolated operation or interconnected with the local network, is the main motivation for this paper.

The acceptance of MGs and their viability are significantly related to economic issues. One of the most important aspects of the MG's economy is the relationship to the local electricity distribution system. In fact, as previously mentioned, the MG can operate connected to the distribution network, through an underground or overhead cable of LV or MV, depending on the voltage level of the network, or in isolated mode, fed by local generation [4].

The main objective of this paper is to identify and evaluate the situations in which it is economically advantageous to build an interconnection line to the local network. The evaluation parameter is the Levelized Cost Of Energy (LCOE) [5]. This indicator is usually used to calculate the cost of producing electricity in a power plant, but, in this paper, this concept is extended to be applied to the cost of energy transmission in a power line, including fixed cost, variable cost and cost of losses.

To this purpose, an economic analysis model was built, whose inputs are the different costs and the output is the LCOE, for each simulated case-study. The case-studies include MGs with three different sizes (number of consumers), different generating technologies (diesel, natural gas, PV + battery) and different types of interconnection line (LV or MV, overhead or underground line).

The rest of this paper is arranged as follows. The proposed economic model is discussed in Section II and analysed and discussed by case studies in Section III. Finally, Section IV presents the main conclusions that can be drawn from the analysis carried out.

II. ECONOMIC MODEL OF ANALYSIS

In this chapter, the economic model developed to assess the economic profitability of the operation of a MG, either in isolated mode or interconnected to the grid is exposed.

We will apply this indicator in an innovative way, that is, in addition to using it in an energy production system, as usually, we will apply it to assess the discounted average cost of the unit of energy transported by a transmission system. This is an extrapolation that makes sense, since the costs associated with the transmission of energy are of the same nature as the costs of an energy generation system. Thus, in this case, the fixed and variable costs of investment in a transmission system, the cost of selling energy to the MG by an external supplier, as well as the cost of losses will be included.

A. Levelized cost of energy (LCOE)

1) General case

The main indicator of the cost of electricity produced during the lifetime of a power plant, whether it is renewable or not, is the Levelized Cost Of Energy (LCOE), which allows to compare different technologies of electricity production. This indicator is given in €/kWh and considers the total costs of an electricity generating system over the lifetime of the system (which includes investment, operating and maintenance and fuel costs, if they exist), per unit of electricity that the system will produce during the same period [5].

The LCOE equation is given as follows:

$$LCOE = \frac{I_t + C_{o.m}k_a + C_{comb}k_a}{E_a k_a} = \frac{\frac{I_t}{k_a} + C_{o.m} + C_{comb}}{E_a} \quad (1)$$

where I_t – Total investment [€], $C_{o.m}$ – Annual operating and maintenance costs [€], C_{comb} – Annual fuel costs [€], E_a – Electricity produced annually [kWh], k_a – Discount factor.

2) Particular case of the transmission line

In general terms, the LCOE is a discounted production cost and therefore has direct application in power generation costs. However, in this paper, the generalization to compute the transmission costs in the case the MG is fed through a line, with the necessary modifications, was considered.

To model the investment cost of the interconnection line, it was considered that the investment could be divided into two components: one component, C_F (€/km), a fixed cost, because it does not depend on the section of the conductors, it depends only on the length of the line (refers to the installation of poles or trenching), and a component, C_V (€/km.mm^2), a variable cost, because it depends on the type of line installed, namely its section (it refers to the cost of the line, itself).

So, in a first step, we can say that the total line investment is

$$I_{t_{linha}} = C_F l + C_V S l \tag{2}$$

Where l – line length [km], S – Line Section [mm^2], C_F – Fixed cost [€/km] and C_F – Variable cost [€/km.mm^2]

Adding to the investment cost referred to above, there is a cost, of a different nature, due to the losses in the line, which is equivalent to a variable cost. It is possible to demonstrate that the cost of losses is given by:

$$C_L = 3\rho \frac{l}{S} I_{ponta}^2 (\Delta t_1 c_p + \alpha^2 \Delta t_2 c_{np}) \tag{3}$$

Where ρ – Resistivity of the material (aluminium or copper) [Ωmm^2/m], c_p – Unit cost of losses at the peak [€/Wh], c_{np} – Unit cost of losses off-peak [€/Wh], Δt_1 – Peak period [h], Δt_2 – Off-peak period [h] and α – load factor

The total line investment, including the cost of losses, is given by:

$$C_{t_{Linha}} = C_F l + C_V S l + 3\rho \frac{l}{S} I_{ponta}^2 (\Delta t_1 c_p + \alpha^2 \Delta t_2 c_{np}) k_r = l\left(C_F + C_V S + C_L' \frac{I_{ponta}^2}{S}\right) \tag{4}$$

Where k_r is the line discount factor.

Taking into account that the optimal section is determined so that the cost is minimum, the optimal section is given by [6]:

$$S_{ótima} = \sqrt{\frac{C_L'}{C_V} I_{ponta}^2} = \sqrt{\frac{3\rho I_{ponta}^2 (\Delta t_1 c_p + \alpha^2 \Delta t_2 c_{np}) k_r}{C_V}} \tag{5}$$

3) General LCOE equation

After all the above mentioned considerations the final equation for the LCOE is:

$$LCOE = \frac{I_t + I_{t_{linha}} + (C_{o.m} + C_{comb} + C_{ve}) k_a + C_L k_r}{E_a k_a} \tag{6}$$

Where C_{ve} [€] is the price of energy supply by an external supplier.

B. Simulation Conditions

In the study performed, three parameters were changed:

- The size of the micro-grid, namely the number of consumers (small, medium and large MG);
- The type of microgeneration (diesel, natural gas and solar PV + battery);
- Type of line connecting the MG to the power grid (overhead or underground cable, LV or MV).

1) Micro-grid size

Table 1 presents the summary of the most important data regarding the considered MGs.

Table 1 – Electrical characteristics of the considered MG.

MG	Number of consumers	Peak Power [kW]	Average Power [kW]	Load Factor	Total Daily Energy [kWh]
Small	10	9	3.4	0.378	81.46
Medium	100	65	34	0.523	816.16
Big	1000	453	322.1	0.711	7730.46

2) Microgeneration type

As for the two types of non-renewable generators, the Natural gas (NG) micro-generator requires a higher initial investment, although on the other hand, operation and maintenance costs and fuel costs are about half that of diesel [7] [8].

The initial investment in a PV generator is much higher as compared to the non-renewable generators, despite the tendency for the PV cost to decrease in the near future. It is noted that the unit investment (€/kW) of PV has decreased sharply in recent years. Due to economies of scale, the unit cost of domestic PV, which we are considering here, is higher than the unit cost of grid-connected PV plants. The cost of fuel is obviously nil in this type of technology. The price of the battery is to be added to the PV system cost. The battery cost depends on its energy storage capacity; hence the cost is given in €/kWh. No operation and maintenance costs were considered for the battery, because it was considered negligible, considering the amounts involved [9].

3) Interconnection line

It should be noted that the fixed costs associated with underground cables are about 5 times higher than those of the overhead lines, in the LV case, and about twice as much, in the MT case. The difference is less pronounced with regard to variable costs [10].

The unit cost of losses is equal to the unit cost of energy in the electricity market because the losses have to be purchased in the market.

In the power line section sizing, two options were assessed, referring to the value of the section to be used:

- Use of a standard section - The following standard sections were used, whether an overhead line or a cable, or whether LV or MV are considered: 25, 50, 120, 240 mm^2. This option intends to reflect the situation in which the line is built to exclusively feed the MG under study.
- Use of the optimal section - The optimal section calculated from equation (5) is used. This situation considers a breakdown of the costs of the line, assuming that the line is shared by several MGs and that to each one is allocated the part of the line section that is actually used.

This last option to choose the line section has a great impact on the calculation of the costs associated with the line, namely on the cost of losses, which will increase, and on the total investment in the line, which will decrease. The cost of losses increases because it is inversely proportional to the section; the investment decreases, because the section decreases, and because, in this approach, it is considered that the fixed cost decreases proportionally with the section, using the following proportion:

$$I_{t_{linha}} = C_F l \times \frac{S_{opt}}{S_{norm}} + C_V S_{opt} l \tag{7}$$

Where S_{opt} – Optimal section and S_{norm} – Standard section.

C. *Economic Model Description*

The starting point is the case of MG powered exclusively by a local generator, i.e. there is no connection to the public power grid. The generator can be diesel, NG or PV + Battery. Each of these cases is a base case, with an associated LCOE, which will be taken as the reference value.

Let us take the example of a MG with 100 consumers, powered exclusively by a diesel generator. The respective daily load diagram (which is equal to the generation diagram, since we are not modelling the power grid, and therefore there are no losses) is shown in Fig.1.

Thereafter, the maximum capacity of the generator will be limited, with the remaining load being fed through the interconnection line to the public grid. In this situation, the generator is no longer able to feed the load alone and, as such, the load is fed through the generator + line assembly. Under these conditions, we will have the situation that is reported in Fig. 2. To this load distribution by the generator and line corresponds a certain LCOE. Lower values than the reference LCOE (calculated for the case where only the diesel generator feeds the load) corresponds to cases where the interconnected operation is advantageous. Higher values mean that the interconnected operation is not advantageous.

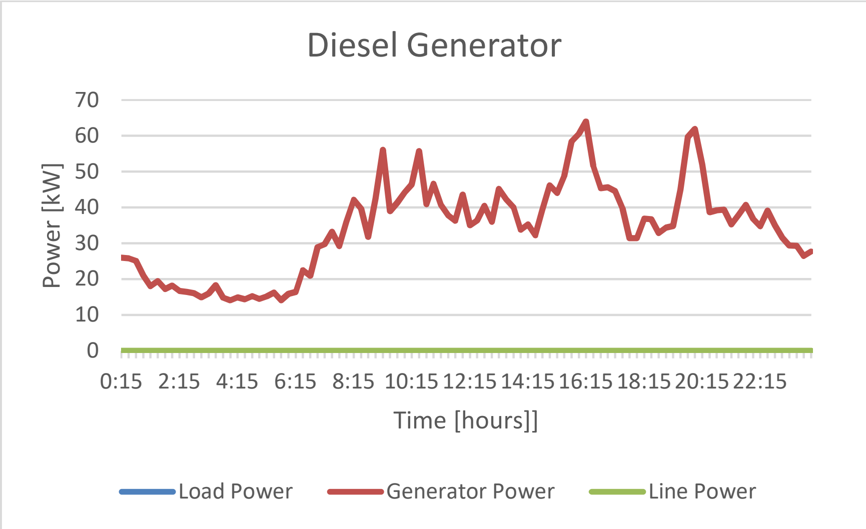


Figure 1 – Example of the daily load and generation diagrams for the diesel case.

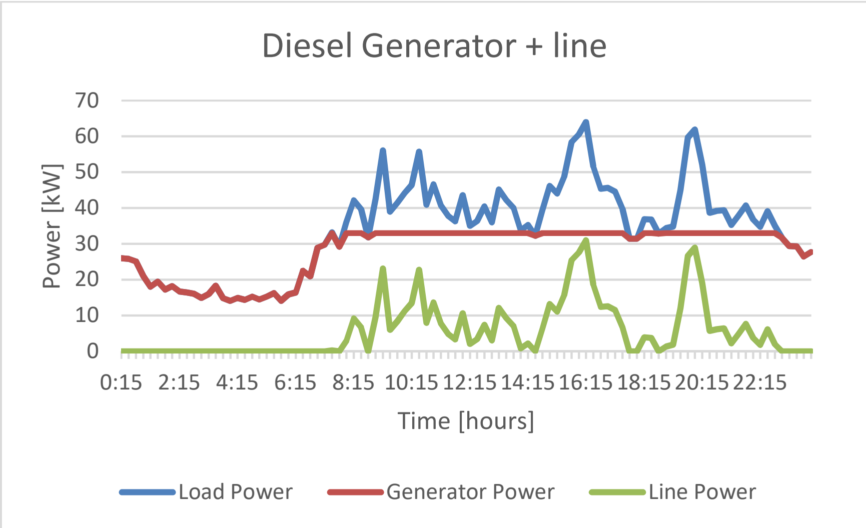
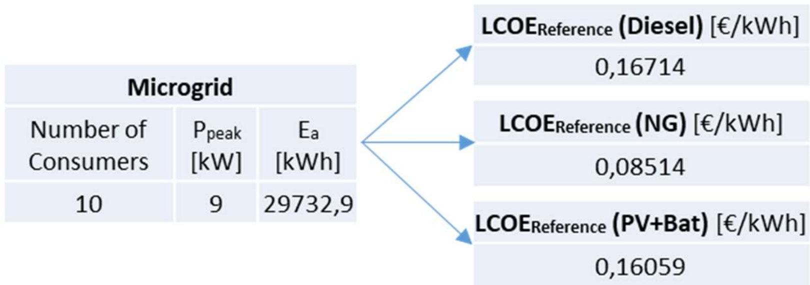


Figure 2 – Example of the daily load and generation diagrams for the diesel + line case.

III. PRESENTATION AND EVALUATION OF RESULTS

A. Reference Case Studies

In Fig.3, the reference LCOE for the 3 types of generators under consideration and for the MG under study (small – 10 consumers, medium – 100 consumers and large – 1000 consumers) are presented.



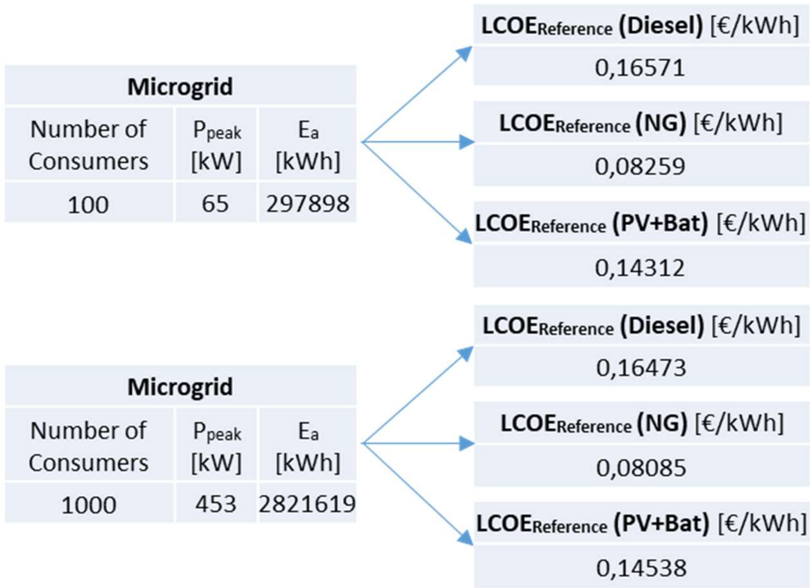


Figure 3 – Reference LCOE for each MG and for each type of generator.

B. *Case Studies*

As previously mentioned, we have assessed two groups of case studies:

1. The first is focused on the situation of a MG powered by a line on an exclusive base. The optimum section is calculated by using the nearest normalized section, which can be 25, 50, 120 and 240 mm^2.
2. The second group reflects the situation of line cost sharing. Thus, the calculated optimal section is used, with each MG being counted only by the percentage of the line section that is actually used.

1) Using the standard section

As an example, we present the graph of Fig.4 which shows the results for the small MG, with a LV line exclusive connection and for each of the local generators considered. In this graph, the evolution of the LCOE is presented when the percentage of the load fed by the generator decreases and, consequently, the percentage fed by the line increases.

As for the diesel generation, the case where the line supplies the entire load corresponds to the most economical LCOE. This is not surprising, since the diesel solution is quite expensive, as it had already been highlighted. In what concerns the NG generation, the installation of a LV line is never economically feasible for these simulation conditions, since the reference LCOE is quite low. To what relates to the PV + battery option, the installation of a LV line is justified for all possible load distributions between the generator and the line, since the reference LCOE is high. The most economical LCOE is achieved in the case where the line is responsible for 75% of the load supply in terms of peak power, and the LCOE increases very slightly when the line supplies the entire load.

From the results presented, it is possible to draw the following general conclusions:

- Diesel is an expensive solution, so the installation of a line soon becomes advantageous for load breakdowns exceeding 50% of the peak power, in the case of small MG; in the case of the medium MG, the best option is to build a LV overhead line and in the case of the large MG, an MV line is justified.
- NG is a very cheap solution. For the simulated conditions tested, the installation of an overhead line is never justified, even in the case of the large MG.
- The solar PV + Battery solution has a LCOE similar to the diesel solution, therefore the installation of a LV line is the best option for small and medium MGs and one MV line for large MG.

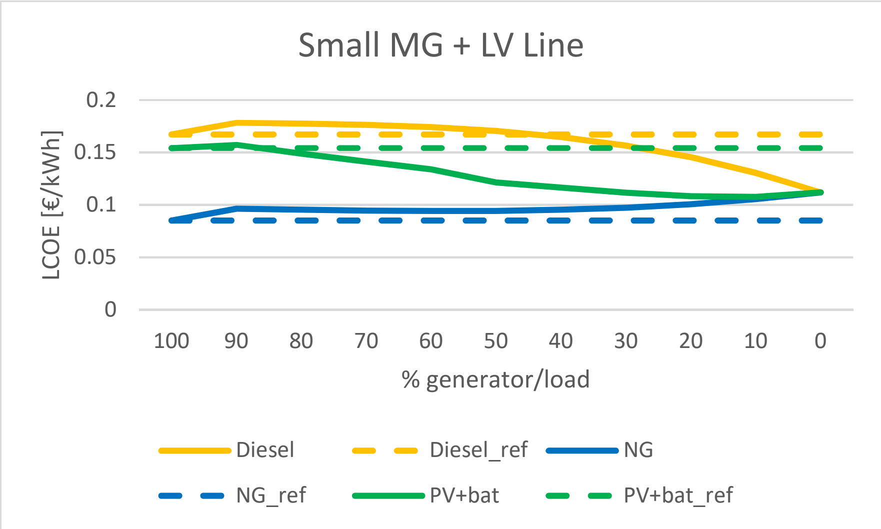


Figure 4 – LCOE evolution ; small MG + exclusive LV line for different types of generation; standard section.

2) Using the optimal section

As an example, we present the graph of Fig.5, which shows the results for the small MG, with a shared LV line connection and for each of the local generators considered. In this graph, the evolution of the LCOE is presented when the percentage of the load fed by the generator decreases.

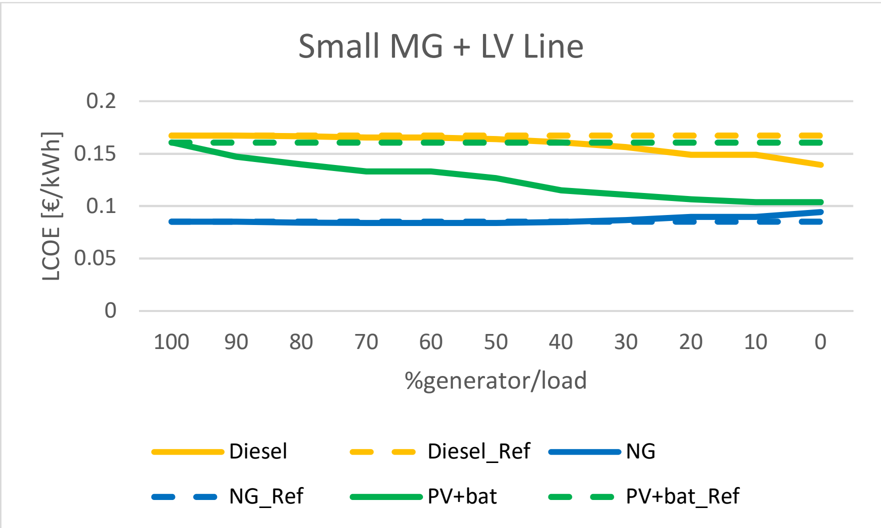


Figure 5 – LCOE evolution ; small MG + shared LV line for different types of generation; optimal section.

In this situation, the investment in the line is reduced, so the construction of a shared line becomes economically feasible as compared to the situations in which the installation of an exclusive line did not compensate. For the diesel and solar PV + Battery the shared LV line is always the best solution; as for the NG generation, the LCOE is quite similar either in isolated operation or in shared interconnection.

It is interesting to note the increase in the cost of losses due to the reduction of the section. However, the increase in the cost of losses is much lower than the reduction in investment, which is why there is a significant reduction in the total cost charged to the line. For example, by analysing the case of the LV line supplying the small MG integrally, the standard section is found to be 25 mm^2 and the optimal section is 18.04 mm^2. The cost of investment decreases in this proportion and the cost of losses (which has a much lower weight) increases by the same proportion.

C. Sensitivity Analysis

We made a sensitivity analysis of the variation of the fuel cost for the case-studies with diesel and NG generators. This sensitivity study intends to take into account the transportation, distribution and storage costs of the fuel. In this way, we analysed the situation in which the cost of fuel was increased by 50%, in both diesel and NG generation cases.

It was concluded that this variation in fuel costs has a significant influence on the LCOE increase, when compared, for example, with the variation imposed on the generator investment, that we have also assessed. In relation to the case of the diesel generator, this variation in fuel cost does not have a significant impact in the overall conclusions, because in the reference situation, the interconnection was already the good solution. This conclusion is reinforced now, in which the cost of fuel increases. In the case of the NG generator, the situation is different. In the reference situation, the NG generation has a very low LCOE and the construction of the line rarely compensated. With this increase in fuel costs, LCOE will increase and the line becomes an economically more viable solution, especially in larger MGs.

IV. CONCLUSIONS

In this work, an economic model for MG analysis was developed. This model allows to evaluate the most economical mode of exploration: isolated operation or interconnection to the local distribution grid. The developed model uses the LCOE – Levelized Cost of Energy – as the evaluation indicator. In this context, a general expression of the LCOE calculation was proposed, which may be applied not only to the cost of electricity production, but also to the cost of electricity transmission through a power line and the cost of purchasing energy from the external supplier. The discounted production cost (the LCOE) includes investment, operating and maintenance costs, and fuel costs, where applicable. The LCOE associated with the interconnection power line includes the cost of the line, namely fixed costs with trenching or installation of poles, variable costs related to line or cable installation, cost of losses and cost of the electricity external supply.

The combination of all these variables takes on gigantic proportions, so we have constructed and analysed the most plausible scenarios with the best estimate for the various costs involved. Out all of the simulations carried (the results of most of them are not shown in this paper), using a specially designed tool, it was possible to draw the following conclusions:

- The production solution composed of diesel generators is a globally costly solution, so that the installation of a LV interconnection overhead line is advantageous for line-generator load allocations greater than 50% of the peak power, in the case of the small MG; in the case of the medium MG, the best option is to build a LV overhead line and in the case of the large MG, a MV overhead line is justified.
- If the MG owns natural gas fired generators, it was observed that, at current reference prices, this is a very cheap solution. The installation of an overhead line is never justified (under the tested conditions), even in the case of a large MG. It should be noted that at, this point, no distribution costs were considered and that the current price of oil reflects the low costs associated with natural gas.
- The generation option made up of an association of solar PV generator and battery has a LCOE similar to the diesel option, therefore the installation of a LV line is the best option for the small and medium MG and a MV line is the right solution for the large MG.

Although the results were not shown in this paper, simulations were performed using underground cables instead of overhead lines. The costs associated with the installation of underground cables are much higher than those of the overhead lines, so it was found that their construction is not economically justified. However, reliability is increased and the environmental impact is low, so an analysis considering these parameters could lead to different results.

A simulation was also performed, in which the installation costs of the line were considered to be spread over several MGs. In this case, the value of the calculated optimal section was used instead of the nearest normalized section. This option resulted in a marked decrease in the investment cost of the line and a moderate increase in the cost associated with the losses, which does not compensate for the decrease in investment. The conclusion is a decrease in the total costs of the line, which will increase the number of situations in which the installation of a line to supply the MG is the most economical solution.

As the cost estimates are not entirely reliable and a cost reduction of the solar PV solution is to be expected in the near future, a sensitivity analysis was carried out on the various costs involved. To this end, the investment costs in production technologies and the fixed and variable costs of the interconnection line were varied by more or less 50%. Fuel distribution costs were not initially considered, but they are an important factor, especially if we are studying MGs located in remote places, which can dramatically increase fuel costs. Thus, a sensitivity analysis was performed, this time in the form of a 50% increase in fuel costs of diesel and natural gas.

The main conclusions drawn from the sensitivity analysis can be summarized as follows:

- The increase or reduction of costs in the solution composed by diesel generators does not have a marked influence on the profitability of this option. The installation of a LV overhead line, in the case of small and medium MG, and MV in the case of large MG, remains the right choice.

- Variation in investment costs in the natural gas generator does not change the conclusions regarding the reference situation. This solution is globally inexpensive, the installation of a line never being the right option (for the conditions tested).
- For the solar PV generator solution associated with a battery, only cost reductions were considered, according to what is currently expected to occur in the future. It has been found that a strong reduction in investment costs makes this option economically attractive, therefore not requiring the construction of interconnection lines. If the reduction of investment costs is only moderate, the installation of an interconnection line still makes sense.
- The variation of fixed and variable costs of the line has implications for the situations in which its installation is justified. When the investment costs are increased, the construction of the line is more difficult to recommend, although it continues to be justified in the case of the diesel generator and in the case of the solar PV + battery. When the investment costs on the line are reduced, it is easier to justify its construction. Note that in the case of the natural gas generator, the reduction of line costs is still not enough to recommend the installation of the interconnection line.
- The increase in fuel costs had a major influence on results and the construction of the line became a more viable option. These results were especially interesting for the cases with a natural gas generator, which, while in the reference situation constituted a very cheap solution, after this increase the line became, in many cases, the best option for feeding the load.

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