

Long-Term Planning of Industrial Microgrids

Charline Stevanoni, François Vallée,
Zacharie De Grève and Olivier Deblecker
University of Mons, Faculty of Engineering
Electrical Power Engineering Unit
Boulevard Dolez 31, 7000 Mons, Belgium
Email: charline.stevanoni@umons.ac.be

Pascal Couneson
Decube Consult
Quai du Pont Canal 3,
7110 Strépy-Bracquegnies, Belgium
Email: p.couneson@decube.be

Abstract—This paper deals with the context and objectives of the long-term planning of industrial microgrids. A first flowchart for the development of a tool helping to the setting up of industrial microgrids is presented. The imagined methodology allows taking into account the different (possibly conflicting) objectives of the microgrid stakeholders, by seeking an equilibrium from a game theoretical perspective. Beforehand, the role of each stakeholder as well as the decisions they can take have to be well-defined through an interaction model. The description of such an interaction model is developed in this paper.

I. INTRODUCTION

In order to respond to the plan "20-20-20" decided by the European Union and to the current society willingness of moving towards a greener environment thanks to the reduction of nuclear electricity production, recent years have witnessed a large deployment of Renewable Energy Systems (RESs). The network has therefore undergone a change of paradigm in which the electricity production is not centralized anymore but distributed in the network. However, the proliferation of RESs is limited because of the intermittent operation of some of them, such as solar photovoltaic (PV) and wind generation units. Those fluctuating energies may cause troubles in transmission and distribution networks. Moreover, the fixed loads of the network have to be fed continually and may not face a lack of supply. Those reasons involve that the proliferation of RESs is not possible without a smart management [1] and the use of Energy Storage Systems (ESSs) to allow flexibility. In order to integrate new productions and load management in the network, the notion of microgrid is more and more widespread. According to [2], a microgrid is "a group of interconnected loads and distributed energy resources (DERs) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes". In this definition, DERs include distributed generations (DGs), RESs and ESSs. Microgrids are more than simple backup generation because they can provide a wide range of benefits at a larger scale and they are more flexible [2]. Indeed, microgrids can be used as a support for the distribution network performance such as reliability, resiliency and power quality. The installed microgrid world's capacity was about 1.1 GW in 2012 and is estimated to

be 4.7 GW in 2017 [2]. In Europe, microgrids that are often developed in existing networks must be adapted to the existing configuration and are connected to the general network. However, the microgrid development is also more and more intended in emerging countries without initial infrastructure such as in Africa. In this case, they are built from nothing and operated in island mode [3].

In this work, grid-connected microgrids are considered at a Medium Voltage (MV) industrial level and not at a residential one. A motivation for industrial microgrids development is to decrease the electricity bill for companies which take part to the microgrid. Indeed, the MV electricity purchase price is more and more expensive for industries, especially in Belgium. A survey conducted in 2016 showed that, for belgian industrial companies, their electricity bill is 16 to 40 % more expensive than the mean one of the neighbour countries (France, Holland and Germany) taking into account taxes and network costs which are also consequent in Belgium, as shown in Fig. 1 [4].

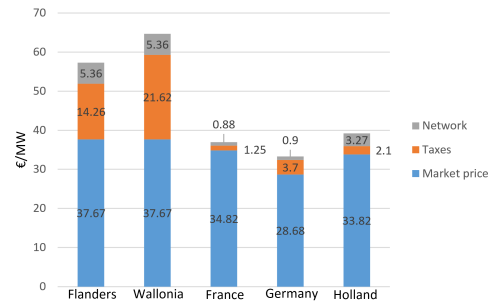


Fig. 1. Electricity Price in 2016 (€/MWh) (profil baseload 100 GWh) [4].

Therefore, investing in decentralized generation such as wind or PV may become interesting for industrial companies. The industries which install those kinds of productions want to improve their self-consumption, *i.e.* to make profitable their investment by trying to consume locally all their generated electricity and, consequently, to avoid selling it at a cheaper price than the one paid for direct consumption from the grid. Indeed, the excess of generation is sold to the distribution network at a very low price (market price) compared with the purchase price (market price + taxes + network price).

As an example, the company partially funding this work previously invested in a PV installation of 250 kWp. However, after a few years of operation, the objective of 100% self-consumption has not yet been achieved due to the high variability of sunshine in Belgium. Indeed, PV generation was sometimes not sufficient to fully supply the consumption, whereas reverse power flows occurred at other times. For such an installation, the residual produced electricity has to be sold to the distribution network, but the selling price is very low compared to the purchasing one. Such a difference represents a shortfall for the company. One way to reduce it is to consider electricity storage facilities. However, a first study has shown that storage batteries are still too expensive to be cost-effective for a single company [5].

At a larger scale, in an industrial estate, the consumption profiles of the companies can be complementary. The installation of a single storage unit shared among several companies could therefore be more profitable. In such an industrial estate, in which several companies would massively invest in RESs, a pooling of the production units could be considered in a microgrid framework. However, the companies would like to know if such a microgrid could be profitable over the years considering their wish to keep a connection with the distribution network and the costs that this involves. In order to meet this demand, it is necessary to plan at a long-term horizon (typically up to 20 years) the evolution of the microgrid. In this context, the present work aims at providing a tool for the setting up of industrial MV microgrids with a minimization of the electricity costs while taking into account the individual (possibly conflicting) objectives of the microgrid stakeholders.

This paper is organized as follows. In section II, the methodology of the long-term planning tool is described, including the management of the microgrid and the costs objective functions formulation. Section III then presents a first model of interaction in detail *i.e.* the role of each stakeholder and the decisions they can take. Finally, conclusions are drawn and perspectives for future work are given.

II. METHODOLOGY OF THE LONG-TERM PLANNING TOOL

In an industrial microgrid, several parties have to be considered. These are the individual prosumers (which are the consumers who possibly own their local RESs), the Distribution System Operator (DSO) and the Industrial Estate Operator (IEO). In this contribution, the microgrid is managed by an aggregator. One of the goals of this work, which is also one of its originalities, is to put as aggregator each stakeholder of the microgrid alternately. Depending on the aggregator, the management strategy of the microgrid will be different. In addition, two additional strategies are considered in which the aggregator is, respectively, an independent entity or a state organization. Those strategies are detailed in this paper. Moreover, for each stakeholder of each strategy, an

annual objective function Va_N is written and a global objective function NPV for Net Present Value is written over N_{tot} years.

A. Costs objective function formulation

The annual objective function Va_N for each stakeholder is the net Value for year N , which is defined by Eq. (1) as the difference between the revenues and the expenses during the year N . This expression (inspired from [6]) has two parts: an hourly part (terms in parentheses) and an annual part.

$$Va_N = \left(\sum_{h=1}^{h=8760} (R_{h,N} - C_{h,N}) \right) - Cm_N - Cs_N - Ci_N \quad (1)$$

where $R_{h,N}$ and $C_{h,N}$ are, respectively, the revenue and cost per hour, Cm_N is the annual maintenance cost, Cs_N is the annual additional cost and Ci_N is the annual investment cost.

In order to analyze the profitability of the microgrid over N_{tot} years, the NPV is used because costs and revenues in year 1 are not equivalent to those of the future, as time has an impact on the value of cash flows. After computing Va_N for year N , the Present Value (PV_N) is computed taking into account the discounting of future cash flows through the discount rate i and they are cumulated over the planning time horizon of N_{tot} years to obtain the NPV (2):

$$NPV = \sum_{N=1}^{N_{tot}} PV_N = \sum_{N=1}^{N_{tot}} \frac{1}{(1+i)^N} Va_N \quad (2)$$

Thus, a positive NPV indicates that the project is making benefits over the planning period.

B. Strategies

The goals pursued by each aggregator are described in this part. They differ by the direct benefits they expect from the microgrid (sign of the NPV).

Strategy I (aggregator = DSO): The DSO intends to make benefits by decreasing transmission costs, even if the microgrid client electricity bill is expected to decrease. Its role is also to maintain or improve the quality of the electricity in the distribution system and in the microgrid and to ensure their stability $\Rightarrow NPV > 0$;

Strategy II (aggregator = a single or a group of prosumers): They want to make benefits thanks to a reduction of the difference between the actual purchasing price of electricity to supply their needs and the actual selling price of the excess of electricity produced by their RESs. In that way, an improvement of their self-consumption, *i.e.* a decrease of the electricity amount exchanged with the distribution network, is pursued. They can also provide services to the DSO to obtain an extra revenue $\Rightarrow NPV > 0$;

Strategy III (aggregator = IEO): IEO wants to optimize the proper operation of the microgrid by promoting the RESs of the prosumers. Its first interest is not to make direct

benefits but to provide a social global welfare and to develop its industrial estate by attracting new companies in the area thanks to an attractive price of electricity (socio-economic dimension) $\Rightarrow NPV <, = \text{ or } > 0$;

Strategy IV (aggregator = an independant entity): Its objective is to make pure benefits thanks to a maximization of the revenues coming from the microgrid and the optimization of its proper operation $\Rightarrow NPV > 0$;

Strategy V (aggregator = a state organization): Its objective is to manage the microgrid with the goal of optimizing its proper operation and keeping a social global welfare between all the stakeholders without making any benefits $\Rightarrow NPV = 0$.

In conclusion to this point, it is obvious that the choice of the aggregator will influence the decisions to be undertaken in the management process of the microgrid.

C. General organization of the decision-making tool

Each management strategy described above is studied under a large number of scenarios [7] which represent possible evolutions of the microgrid in terms of consumption and production profiles, as well as in terms of new RESs by the prosumers (note that RESs are supposed to be only placed by the prosumers and not by the DSO). Each scenario is created on a planning period of 20 years (which approximately corresponds to the life time of RESs). For each hour of each scenario, a load flow is performed and the state of the microgrid is defined through technical [8] and reliability [9] indicators. At the end of the load flow, the flowchart presented in Fig. 2 is applied. The aggregator and the stakeholders recover all those indicators and analyze them. Each one will have to choose between several decisions among the possibilities arising from the interaction model of the concerned strategy, such as investments or flexibility services. Every decision is associated with a price that has to be taken into account in (1) and, thus, in (2) over 20 years. Following the level of benefit, those decisions are classified in a preference order. Practically, the final decision will be found thanks to the computation of an equilibrium between all the stakeholders using a game extracted from the Game Theory [10].

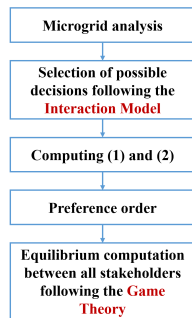


Fig. 2. Flowchart for each microgrid stakeholder (including the aggregator).

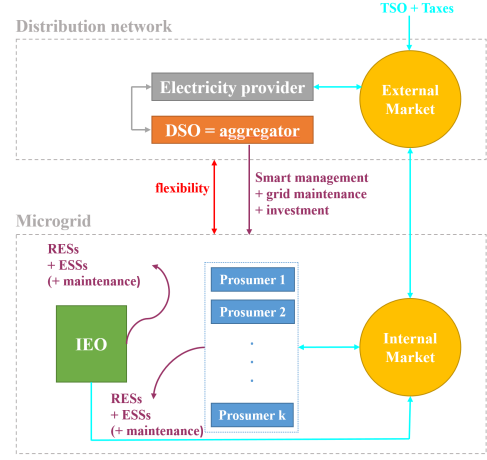


Fig. 3. Interaction model for strategy I.

III. A FIRST INTERACTION MODEL

For each strategy, it is necessary to define the interaction model between all the stakeholders (with their roles and decisions), as well as to establish the cost terms in detail. In this paper, an interaction model for the first strategy (aggregator = DSO) is presented (Fig. 3). There are three kinds of interactions: cyan arrows represent interactions related to the cost of electricity exchanged through the External Market (EM) and the Internal Market (IM), the red double arrow represents flexibility services and the purple arrows depict the microgrid development.

A. Electricity exchanges

The privileged electricity exchanges are those inside the microgrid. The prosumers who own a RES use their own generation in the first instance. Three cases can then appear for each prosumer. In the first situation, the production and the consumption are equal and the balance is respected. In the second case, there is more generation than consumption and, consequently, the prosumer needs to sell its electricity surplus (*prosumer = seller*). In the last configuration, generation is lower than consumption and the prosumer has to buy electricity through the aggregator (*prosumer = buyer*). For the first case, there are no exchanges but, in the two other cases, exchanges have to be managed by the aggregator in the IM. As shown in Fig. 4, each seller gives a minimal price at which he accepts to sell its electricity surplus and each buyer gives a maximal purchase price at which he accepts to purchase the electricity to fully provide its own consumption. Those bounds are then centralised by the aggregator. In this work, the optimization part done in the IM is not handled and will be considered as a "black box". The outputs of this black box are purchase ($Pr_{purchase,\mu}$) and sale ($Pr_{sale,\mu}$) prices at which prosumers can buy and sell electricity inside the microgrid. Those prices are computed in such a way that the aggregator is paid for its operator role by a fee $Pr_{fee,IM}$, which is a percentage of the difference between $Pr_{purchase,\mu}$ and $Pr_{sale,\mu}$.

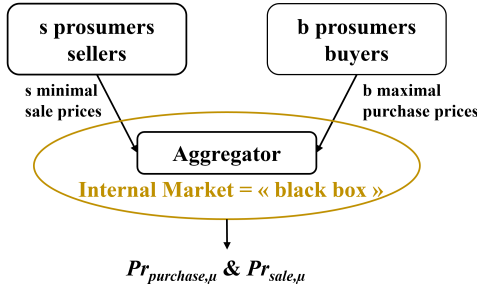


Fig. 4. Electricity exchanges inside the microgrid.

When the exchanges inside the microgrid are done, there are three possibilities: either there is a balance (all the generation is used and all the consumption is provided inside the microgrid), or there is still an electricity surplus (more global generation than the global consumption) or there is a lack of electricity (the global consumption is higher than the global generation). In the two last cases, it will be necessary to have exchanges between the microgrid and the distribution network. Fig. 5 shows how the costs of those exchanges are defined.

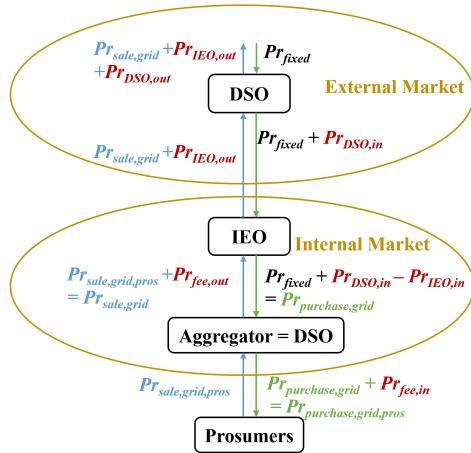


Fig. 5. Electricity exchanges between the distribution network and the microgrid.

The case with a lack of electricity in the microgrid is presented using the green arrows (on the right part of Fig. 5). In the EM, Pr_{fixed} is the base price of electricity with the transmission costs and state taxes. To that price, the DSO adds the distribution cost ($Pr_{DSO,in}$), but since the aggregator is the DSO here, it can be imagined that this price will be flexible (the DSO can decide to put it equal, higher or lower than the classical actual price). Then, in the IM, as one objective of the IEO is to make electricity price more interesting for the prosumers, IEO could help to reduce the electricity purchase price thanks to a contribution $Pr_{IEO,in}$. As a result, the electricity purchase price $Pr_{purchase,grid}$ is paid by the aggregator. The aggregator then grants himself with a fee $Pr_{fee,in}$ and sells the electricity to the prosumers according to their needs ($Pr_{purchase,grid,pros}$).

Consider now the case in which there is an electricity surplus from the microgrid. This exchange is presented by the blue arrows in Fig. 5. First, the prosumers give to the aggregator their selling price ($Pr_{sale,grid,pros}$). Then the aggregator puts its fee ($Pr_{fee,out}$) and the selling price of electricity is defined ($Pr_{sale,grid}$). Afterwards, the IEO takes back a flexible part of its contribution through the increasing of the selling price with the value $Pr_{IEO,out}$. Finally, in this particular strategy with the DSO as aggregator, the DSO adds its distribution cost $Pr_{DSO,out}$ in the EM. Note that the prices in red on Fig. 5 are flexible, *i.e.* their values depend on the decision of the concerned stakeholder.

B. Flexibility services

In reference [11], the flexibility is defined as a "modification of injection or consumption in reaction to an external price (from the DSO) or to the activation of a signal in order to provide services". The red double arrow in Fig. 3 represents the flexibility services exchanges between all the stakeholders from the distribution network and from the microgrid. For an easier understanding of those services, they are summarized in tables inspired from [12] and are divided between the microgrid needs (Table I) and the distribution network needs (Table II). In those tables, the second column indicates which service(s) can be done to cater the needs. The third column indicates how the service is managed and the last two columns specify the provider and user of the service, respectively. Note that when the provider or the user is the aggregator, it can be either on its behalf or on behalf of prosumers. In the second case, the aggregator charges a fee as operator of flexibility service and the costs or the revenues are shared between the concerned prosumers. In the economical record, the costs linked to flexibility services have to be compared with investment costs to make the more profitable choice.

From the microgrid point of view (Table I), the first need is obviously the electricity which can be provided either by the distribution network or by other prosumers inside the microgrid. The exchange mechanisms are those explained in section III. A. The second need is to avoid congestion and an oversize of the microgrid. There are several ways to supply this need such as the adjustment of the RES generation and the load shifting of some prosumers. The goal of this service is to allow the aggregator to avoid investments inside the microgrid such as line reinforcement or reconfiguration. A special contract is done between the prosumers and the aggregator in order to fix the cost and the conditions of that service. Another service is the voltage control inside the microgrid. Indeed, overvoltage can damage prosumer's equipments. This voltage control is done locally by prosumers thanks to the management of active and reactive powers. Again, this service is managed by the aggregator who will take a fee. The penultimate service is the management of the RESs and ESSs by the aggregator. When the aggregator is the DSO, it knows the production and consumption previsions and thus he has to manage the RESs and ESSs integration in order to maximize it. Another way to

maximize prosumer's RESs and ESSs could be investment aids from the IEO. Finally, the IEO profits are the development of the IEO's industrial estate thanks to attractive electricity prices from the aggregator which will allow a cheaper electricity bill to the companies. In that way, the IEO has interest in providing a budget for the growth (new jobs) or the attraction of new businesses.

TABLE I
FLEXIBILITY SERVICES - MICROGRID NEEDS

Microgrid needs	Service(s)	Procurement mechanism	Provider	User
Electricity	Supply electricity from general network	Contract (markets)	Electricity provider	Aggregator (=DSO) on behalf of prosumers
	Supply electricity from RESs and ESSs	IM	IEO or some prosumers	
Congestion management and avoid oversizing	Generation adjustment, load management and peak shifting	Contract	Prosumers	Aggregator (=DSO)
Local voltage control	Active and reactive power provision	Contract	Aggregator (=DSO) on behalf of prosumers	Aggregator (=DSO) on behalf of prosumers
Maximizing RESs and ESSs integration	Prevision production	Aggregator's role	Aggregator (=DSO)	Prosumers
	Investment aids	Contract	IEO	
Industrial development	Attractive electricity prices	Contract (markets)	Aggregator (=DSO)	IEO

From the distribution network point of view (Table II), note that the provider is always the aggregator who charges a fee as flexibility operator and divides the remaining benefits to some prosumers according to their participation in the provided service. The user is always the DSO, not in its aggregator's role but in its classical role. The first service is the supply of electricity by the microgrid if there is a surplus of RESs generation or some electricity from ESSs. The second service is the congestion management in the distribution network which is possible thanks to a management of the microgrid injection and its global consumption regulation. The last service is the voltage control at a larger scale which is possible thanks to the management of active and reactive powers exchanged by the microgrid with the main electrical network.

C. Economical record

This part summarizes in detail all the terms of Eq. (1) for each stakeholder in this investigated strategy (with the

TABLE II
FLEXIBILITY SERVICES - DISTRIBUTION NETWORK NEEDS

Distribution network needs	Service(s)	Procurement mechanism	Provider	User
Electricity	Surplus from RESs and ESSs	Contract (markets)	Aggregator (=DSO) on behalf of prosumers	DSO
Congestion management and avoid oversizing	Adjust injection from microgrid, microgrid global consumption regulation	Contract	Aggregator (=DSO) on behalf of prosumers	DSO
Voltage control	Active and reactive power provision	Contract	Aggregator (=DSO) on behalf of prosumers	DSO

DSO as aggregator). Eq. (1), and thus Eq. (2) after N_{tot} years, has to be written and computed for the aggregator, for all the prosumers and for the IEO. Note that, in this particular strategy, all the expenses and revenues linked to the DSO's aggregator role and its classical role have to be taken into account separately (even if there will probably be some balances). The terms for the aggregator are described in Table III and those for all the prosumers and the IEO are presented in Table IV.

For the aggregator (Table III), the revenue term takes into account all the contributions described above, *i.e.* the revenues linked to the classical role of the DSO through the billing of distribution services which is variable following its decision ($Pr_{DSO,in}$ and $Pr_{DSO,out}$), the flexible revenues linked to its role of IM operator ($Pr_{fee,IM}$, $Pr_{fee,in}$ and $Pr_{fee,out}$), the revenues linked to its role of flexibility services operator (services that it manages for the prosumers) and also revenues thanks to provided services. The hourly costs are those for the use of flexibility services. The last three terms take into account the costs linked to the development of the microgrid (smart management and investments) and its maintenance. For the prosumers (Table IV), the revenues are those linked to the sale of electricity outside and inside the microgrid ($Pr_{sale,grid,pros}$ and $Pr_{sale,\mu}$), as described in the electricity exchanges, and the revenues related to the supply of flexibility services described in previous tables. The hourly costs are structured in the same way, *i.e.* the costs linked to the purchase of electricity outside and inside the microgrid ($Pr_{purchase,grid,pros}$ and $Pr_{purchase,\mu}$) added to the costs of the flexibility services that are used. The investment and maintenance costs are those related to the RESs and ESSs. In addition, for the last three costs, it is considered that prosumers participate for a percentage of the aggregator costs to develop

the microgrid (contract between the stakeholders). For the IEO (Table IV), the revenues are, on the one hand, $Pr_{IEO,out}$ defined above as a recovery of money when electricity is sold to the distribution network and, on another hand, the supply of electricity (flexibility service) thanks to their potential RESs and ESSs. Note that in this last case, their selling price is identical to the one of the other prosumers (IEO takes part to the IM on the same level as another producer). The hourly cost is $Pr_{IEO,in}$ which represents its contribution to the reduction of the electricity price inside the IM when the electricity is purchased to the EM. The maintenance costs are related to its own RESs and ESSs, whereas investment costs could also be related to investment aids provided to prosumers. An additional annual revenue is taken into account in the Cs_N 's row thanks to the industrial development. Note that this last revenue is not an hourly revenue and is consequently considered as a negative annual additional cost. Moreover, $Pr_{IEO,in}$ and $Pr_{IEO,out}$ could possibly be equal to zero.

TABLE III
DETAILS OF THE COST TERMS FOR THE AGGREGATOR

Terms	aggregator = DSO
$R_{h,N}$	$Pr_{DSO,in} + Pr_{DSO,out} + Pr_{fee,IM} + Pr_{fee,in} + Pr_{fee,out}$ + flexibility provider + fees as operator of the flexibility services
$C_{h,N}$	Flexibility user
Cm_N	Grid maintenance + ESSs maintenance
Cs_N	Grid intelligence
Ci_N	Shared ESSs + lines reinforcement + microgrid reconfiguration

TABLE IV
DETAILS OF THE COST TERMS FOR THE OTHER STAKEHOLDERS

Terms	Prosumers	IEO
$R_{h,N}$	$Pr_{sale,grid,pros} + Pr_{sale,\mu}$ + Flexibility provider	$Pr_{IEO,out}$ + Flexibility provider
$C_{h,N}$	$Pr_{purchase,grid,pros} + Pr_{purchase,\mu}$ + Flexibility user	$Pr_{IEO,in}$
Cm_N	RESs and ESSs maintenance + % aggregator's Cm_N	RESs and ESSs maintenance
Cs_N	% aggregator's Cs_N	(-%) of industrial development (=revenue)
Ci_N	RESs + ESSs + % aggregator's Ci_N	RESs + ESSs + investment aids

IV. CONCLUSION AND FUTURE WORK

This paper deals with the planning of an MV industrial microgrid connected to the general network. As many stakeholders take part into those kinds of microgrids, it seems important to consider the objectives and the welfare of each one. The presented methodology includes a microgrid manager called aggregator. The originality of this work is to put as aggregator successively each stakeholder in order to see how

the planning of the microgrid is impacted. Indeed, the choice of the aggregator will influence the decisions to be undertaken in the management process. Concerning those decisions, they are defined through an interaction model for each strategy. This paper described only the case in which the aggregator is the DSO. This interaction model summarizes the electricity exchanges, the flexibility services between the microgrid and the distribution network and details the economical record for this strategy. Thanks to this interaction model, possible decisions are defined, attached to a cost and can be compared. The computation of the Net Present Value defined in this paper for each stakeholder, including the aggregator, allows the ranking of those decisions in a preference order and a final equilibrium can be computed following the Game Theory rules. Currently, the imagined tool is deterministic but the objective of the work is to make preventive planning taking into account all the possible uncertainties as the installation of RESs within the microgrid.

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