Long-Term Planning of Connected Industrial Microgrids: A Game Theoretical Approach Including Daily Peer-to-Microgrid Exchanges

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***Abstract*—In this paper, a tool for the long-term (LT) planning, i.e., up to 20 years, of industrial microgrids (IMGs) connected to the distribution network and made of industrial consumers, prosumers, and of the distribution system operator (DSO), is proposed. The DSO assumes here the new role of microgrid energy manager. In order to realize the proper choice of LT investments (e.g., in renewable energy system and energy storage system), a short-term (ST) energy management is performed each day of the planning period. For that purpose, a new system of daily operation including industrial load management and allowing peer-to-microgrid as well as external energy exchanges is implemented. The LT investments and ST operational decisions are coupled via two game theoretical frameworks, which also allow the modeling of the different, even conflicting, objectives of the stakeholders. Different LT and ST pricing schemes are also considered in order to provide general advices concerning the creation of new IMGs. The developed tool is tested on a virtual IMG and the technical and economical outputs are presented.**

***Index Terms*—Game theory, industrial microgrid, load management, long-term planning, peer-to-microgrid exchanges.**

NOMENCLATURE

Acronyms

DN	Distribution Network
DSO	Distribution System Operator
ESS	Energy Storage System
GTO	Game Theory Operation
IEE	Internal Energy Exchanges
IEP	Internal Exchanges Probability
IMG	Industrial Microgrid
LM	Load Management
LMO	LM Operation
LT	Long-Term
MGEM	Microgrid Energy Manager
MV	Medium Voltage
NPV	Net Present Value
PP	Purchase Probability
PV	Photovoltaic
REP	Renewable Energy Penetration
RES	Renewable Energy Source
SP	Sale Probability
ST	Short-Term
STEM	Short-Term Energy Management
TEP	Total Energy Purchased
TES	Total Energy Sold
TIC	Total Installed Capacity.

Variables

$\Delta\rho_{N,h}^{ST}$	ST Cash-flow of stakeholder N for hour h
$\lambda_{N,h}$	Hourly remaining load of stakeholder N
$\pi_{\%}$	Ratio between IMG and DN purchasing prices
$\pi_{av,day}$	Price Average over the day
$\pi_{av,LM}$	Price Average over the LM period
$\pi_{d,p}^{peak}$	Peak part of the distribution purchasing cost
$\pi_{in,p,h}$	Hourly IMG Purchasing Price
$\Pi_{in,p}$	Vector of IMG Purchasing Price
$\pi_{in,p}^{peak}$	Peak part of the IMG purchasing cost
$\pi_{in,s,h}$	Hourly IMG Selling Price
$\Pi_{in,s}$	Vector of IMG Selling Price
π_{in}^{met}	IMG Metering Price
$\pi_{LM,h}$	Hourly Weight of Purchasing Price
Π_{LM}	Purchasing Price Weight Vector
$\pi_{out,cst}$	Mean Purchasing Price outside the IMG
$\pi_{out,p,h}$	Hourly Purchasing Price outside the IMG
$\Pi_{out,p}$	Vector of Purchasing Price outside the IMG
$\pi_{out,s,h}$	Hourly Selling Price outside the IMG
$\Pi_{out,s}$	Vector of Selling Price outside the IMG
π_{out}^{met}	DN Metering Price
π_r	Ratio between purchasing and selling prices
$\pi_{t,p}^{peak}$	Peak part of the transmission purchasing cost
$\rho_{N,t}^{ST}$	Accumulated ST Cash-flow of stakeholder N
ρ_N^{LT}	LT Cash-flow of stakeholder N
C	Number of LT combinations of investments
$g_{N,h}$	Hourly remaining production of stakeholder N
$G_{tot,h}$	Total remaining production of hour h
J	Number of ST combinations of decisions
$l_{av,N}$	Load Average over the LM period
$l_{b,N,h}$	Hourly Base Load of stakeholder N

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$L_{b,N}$	Vector of Base Loads of stakeholder N
$l_{N,h}$	Hourly Load of stakeholder N
l_N^{peak}	Load responsibility of N in the IMG peak load
$l_{pr,N,h}$	Hourly Process Load of stakeholder N
$L_{pr,N}$	Vector of Process Loads of stakeholder N
$L_{tot,h}$	Total remaining load of hour h
N_{tot}	Number of stakeholders
$p_{N,h}$	Hourly production of stakeholder N
P_N	Production Vector of stakeholder N
r	Discount Rate
Y_{tot}	Number of years of planning.

I. Introduction

RECENT years have witnessed the deployment of Renewable Energy Sources (RESs) in the residential area as well as in the industrial sphere. The main difference between both sectors is the period of high consumption. Indeed, without a smart management, the main residential consumption occurs during mornings and evenings whereas industrial consumption follows working hours of business days. The integration of photovoltaic (PV) installations for industrial companies seems henceforth very appropriate as the period of production is more congruent with the period of high consumption [1]. However, practically, a company is not able to self-consume all the electricity generated by its PV installation, without an optimal sizing of an energy storage system (ESS) [2] and a smart management of its loads. Differences between production and consumption mainly occur during week-ends, but also during weeks because of the variability of the company activity as well as of the electricity generation. Industrial companies connected to the medium voltage (MV) distribution network (DN) have then the possibility to sell their excess of generation to their electricity supplier. However, the selling price of this electricity only includes the commodity price decreased by some DN costs. Hence, there is an important difference between the purchasing price of electricity, which includes grid costs and taxes, and the selling price of the power excess. This difference represents a shortfall for industrial companies because they buy electricity at the full price at some time, while they sell their electricity excess at a lower price at another time.

In this context of high purchasing price of electricity, the electricity bill of industrial companies can represent a significant part of their expenses and should be decreased. For industrial companies which are prosumers, it can be reduced by two ways. The first one is by decreasing the difference between purchasing and selling prices of electricity. However, in the current regulatory framework, this is not possible while staying connected to the DN. The second way is by improving its self-consumption, either by applying LM in order to fit the consumption profile to the electricity generation, or by investing in an ESS. For other industrial companies, which are simply consumers, their electricity bill could be decreased thanks to a more attractive purchasing price of electricity, combined with the smoothing of their consumption profile (in order to reduce the cost linked to their peak of consumption). Overall, attractive electricity prices together with a massive integration of RESs through ESSs and LM are two key factors for reducing the electricity bill of companies. This can be achieved by forming an Industrial MicroGrid (IMG), run by a MicroGrid Energy Manager (MGEM). This paper deals with the LT planning and the ST management of such IMGs by the use of Game Theory, in order to take into account all the stakeholders with their respective objectives.

More particularly, this work investigates the case where the DSO assumes this new role of MGEM. Indeed, nowadays the DSO must face new challenges such as improving the network operation by decreasing network losses, considering uncertainties on electricity markets, and managing demand response [3], while supervising (or even participate in) the microgrids initiatives which appear in the current context. In that way, microgrid control structures which include the DSOs potential actions, have already been proposed in the literature. Reference [4] focuses for instance on the control aspect of eco-industrial parks and [5] analyses the impact of microgrids connected to the MV network. However, none of those contributions considers the DSO as a full fledge stakeholder inside the microgrid.

Microgrids operation performances have already been demonstrated in [6] and [7]. Energy management systems have also been proposed, mainly for standalone microgrids [8]–[11]. Marzband *et al.* [12] propose a modified energy management system for stand-alone microgrids in order to maximize the use of RESs and the lifetime of ESSs. In [13], a real-time interactive energy management system is developed in order to manage several microgrids connected to the DN. After the management of generation and consumption in each microgrid, their surplus or shortage powers are sent to a central management system which coordinates all of them in order to decrease the global operational cost to fulfill their needs. Regarding the combination of the planning and the energy management of microgrids, decisions have to be taken at different time horizons (e.g., long-term investments and short-term LM). The combination of long and short-term time horizons has also been treated in [14] and [15] by looping the long-term investment problem and the short-term operational management part through an optimization formulation. However, all of them consider the benefits of the microgrid composed of several stakeholders as a whole. In the present work, the energy management includes the possibility of performing LM as well. Such a decision is taken in day-ahead by the MGEM. The originality lies in the fact that this short-term management is coupled with a long-term investment problem in a Game Theoretical framework, in order to take into account the respective objectives of all the IMG stakeholders (prosumers, consumers and the MGEM).

Game Theory is however not new in the field of Smart Grids, and a fortiori in microgrids. The main contributions target most of the time the minimization of the energy costs, for each stakeholder of the community or for the microgrid as a whole. These can nevertheless be classified into two categories which depend on the game action variables employed to fulfill that objective:

- Regulate the generation and consumption in microgrids, in day-ahead and in real-time, using non-cooperative [16], [17] and cooperative [18], [19] games. In [20], a Game Theoretical framework is established to schedule LM inside residential communities for minimizing the energy costs;
- Define the internal electricity prices which maximize the profit of the microgrid [21], [22].

Regarding industrial LM, in [23], Gholian *et al.* try to minimize the peak to average ratio in order to maximize the profit. LM methods presented in [23] and [24] include other parameters such as primary materials, the final products and the wastes. Reference [25] shows that, practically, industrial LM methods can be different according to the industrial process considered.

In this paper, a microgrid planning tool is developed with several originalities compared to the above literature review:

- A new framework for defining IMGs, in which the DSO assumes the role of MGEM, is proposed and properly formalized;
- Inside the IMG, each stakeholder (prosumers with their own RES, consumers and the MGEM) is taken as a full fledge player of the game. Their respective objective functions are adapted in order to solve a multi-agent and multi-objective planning problem considering their different and potentially conflicting objectives;
- LT (investment) and ST (day-ahead scheduling) decisions are jointly made through the coupling between two non-cooperative games, which is one of the key features of the proposed methodology;
- The LM process proposed allows to consider the possible different status of an industrial company (prosumer or consumer) as well as the price variation. It is based on the rescheduling of some industrial processes consumptions (without regulating the generation of RESs), taking into account their related constraints in order to not drastically change the company consumption behaviours. The choice of performing LM or not is taken through the ST game computed each day;
- A peer-to-IMG energy exchange mechanism is defined, in parallel with a DN-to-IMG system. This permits to establish a new attractive pricing scheme inside IMGs which allows participating companies to reduce their electricity bill without drastically change their generation and consumption behaviours;
- Different LT electricity price evolutions are considered, in order to quantify their impact on the proposed IMG pricing scheme. Moreover, the daily price profile adopted by the MGEM for exchanges inside the IMG is defined (besides LM) through the ST game.

The paper is organized as follows. Section II details the concept of IMG and MGEM, as well as the planning problem with its decomposition into two time levels. Section III gives a brief introduction to Game Theory, then justifies and formalizes its application to the present problem with the different time horizons. Section IV presents the application of the developed tool to a virtual IMG connected to the MV network. The last section gathers the conclusions and some perspectives of the described tool.

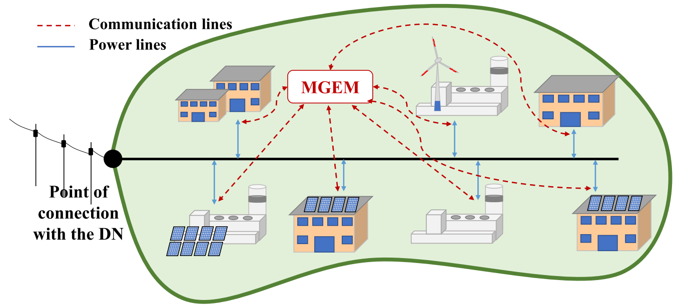

Fig. 1. Representation of an IMG connected to the DN.

II. Planning Problem Definition

The planning problem is defined for an IMG made by an industrial part of the DN, geographically delimited, composed of N_{tot} stakeholders (including the MGEM, $N = 1$), connected by a single point to the DN. The other stakeholders ($N \in [2, \ldots, N_{tot}]$) can be simple consumers or prosumers (with their own RES). As illustrated in Fig. 1, a radial topology is considered for the power lines. Regarding the communication lines, the companies are not directly connected to each other and only the MGEM is collecting and sending information to the participating companies. This allows to respect their information confidentiality and to limit the investments in the communication lines. The role of MGEM is played by the DSO and consists of two new ST main functions:

- Day-ahead forecast of the consumption and generation profiles of the consumers and prosumers. The hypothesis of a perfect forecast is considered here;
- Manage the energy exchanges inside the IMG (peer-to-microgrid exchanges) and with the DN (DN-to-microgrid and microgrid-to-DN exchanges).

The IMG planning has to consider the different time horizons corresponding to the investment decisions and the operational management of the IMG. For that purpose, it is decomposed into two levels (see Fig. 2): the LT one, which is dedicated to LT investments up to 20 years, and the ST one, which is relative to the STEM. The developed tool can typically be used by the MGEM in order to provide LT and ST advices to the stakeholders.

A. Pre-Processing: Inputs Definition

The problem inputs are the electricity pricing scheme, the scenarios which accounts for LT uncertainties such as the yearly evolution of loads and financial parameters, and the companies load profiles and the PV generation profiles.

1) Electricity Pricing Definition: Generally, for a company currently connected to the MV DN, the purchasing electricity price $\Pi_{out,p}$ includes several components:

- Commodity price (energy price);
- Distribution costs (energy and peak parts);
- Transmission costs (energy and peak parts);
- Taxes.

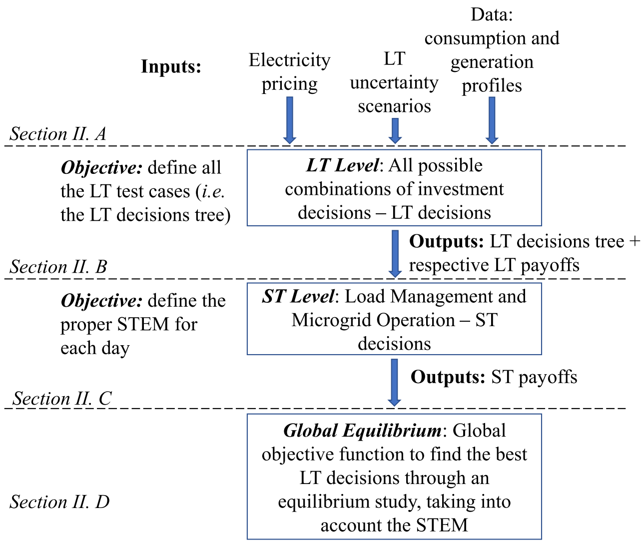

Fig. 2. Planning problem decomposition.

On the other hand, the selling price of electricity $\Pi_{out,s}$ is only composed of the commodity price decreased by some distribution costs.

For an IMG connected to the DN by a single node, two types of pricing are defined. The first one is for the exchanges between the IMG and the DN, and is similar to the one defined above in order to be as fair as possible with the non-participating companies (repartition of the distribution costs). The second one deals with the exchanges inside the IMG. In that case, particular attention must be paid on the tariff structure in order to compensate the potential losses of the DSO (as MGEM). Indeed, if we assume that the network costs are by-passed for exchanges inside the IMG (which is a strong incentive for ensuring companies participation in IMGs), the purchasing price $\Pi_{in,p}$ inside the IMG is composed by:

- The commodity price (energy and peak parts);
- A fee paid to the MGEM for its services;
- Metering costs.

As this pricing is pertaining to exchanges between participating companies inside the IMG, the commodity component is actually the part which is earned by the producer who sells its excess of generation inside the IMG. This component, decreased by the MGEM fee, constitutes the microgrid selling price $\Pi_{in,s}$. Constraints 1 ensure that companies have an economic interest to be a part of the IMG. The ST (i.e., daily) variations of the commodity price will be investigated from two points of view in this paper (fixed or variable prices, see Section II-C1).

$$\Pi_{in,p} < \Pi_{out,p}, \quad \Pi_{in,s} > \Pi_{out,s} \tag{1}$$

Metering costs inside the IMG π_{in}^{met} and between the DN and the IMG π_{out}^{met} must also be taken into account.

2) LT Uncertainty Scenarios Definition: The LT planning is subject to a lot of uncertainties such as the yearly evolution of loads and some electricity prices [14]. Indeed, some companies may further develop their activities, which will increase their consumption. On another hand, the development of new technologies and a better management of companies electricity needs can decrease their electricity consumption. Each company has then an unpredictable LT future consumption. Moreover, the uncertainty also concerns the electricity prices. The commodity and grid costs, along with the taxes, are indeed subject to LT variations paired with the economical and political situation. In order to simply take into account those potential changes, a linear and independent evolution of both consumption needs and electricity prices is considered. They respectively can increase, remain unchanged or decrease. Each combination of such evolutions is called a scenario.

3) Data Pre-Processing and Modelling: Industrial companies may practically have different consumption profiles. In this paper, companies are categorized into two classes: companies with a significant non-shiftable industrial activity (class 1) and companies with a daily controllable activity (class 2). The first class is defined by a consumption profile without seasonality: the industrial activity is running night and day during changing periods (days, weeks or months). For such companies, the application of LM as described in this paper is therefore not feasible. The second class gathers the companies of which consumption profiles follow a fluctuating daily bell-curve. This kind of profile characterises a daily activity with industrial processes during working hours. LM can be considered for this class according to the possibilities offered by the activities and the willingness of the company. According to the class of the companies and the chosen scenario, the data modelling is adapted. For the companies from class 1, each year of available load data is divided into 12 months of 730 hours. Each built year over the planning horizon is composed of 12 months randomly chosen from all available ones. This technique is quite simple but allows to obtain 20 years profiles which faithfully respect periods of activities of the industry.

For the second class of companies, a method inspired from [26] using cumulative distribution functions (CDFs) is used. As the company activity is daily, seven typical days are created (Monday to Sunday) and used to build the 20 years profile. The following steps are performed:

- Same days (of each available year of data) are gathered together. An average profile is computed for each day from the mean hourly value of data for this day (i.e., 7 profiles);
- For each day of the week, 24 hourly CDFs are computed from the difference between the mean hourly value and the corresponding real value (each CDF is built with $52 \times Y_{tot}$ values);
- A sampling on the CDFs is performed. The drawn value is added to the corresponding value from the mean profile.

For generation profiles, the same method (with 24 hourly CDFs for each day) is operated without taking into account the decomposition into seven typical days.

B. Long-Term Investments

Some companies may be reluctant to make investments which are amortized over several years, such as RESs or ESSs. Given the high current prices of such investments, the time of return on investment could be several years according to the consumption profile of the company. Moreover, without taking part in an IMG, this duration only depends on its own activity and on the prices imposed by the electricity supplier. The goal of the LT planning tool is therefore to study the profitability of such investments in an IMG framework, by considering a proper shorter-term management inside an IMG and taking into account the decisions of all the other consumers/producers participating to the IMG. LT investment decisions are taken at year $Y = 1$ by each stakeholder N of the IMG among the following possibilities: invest in a RES, reinforce its existing RES and invest in a ESS. The total cost of each stakeholder N investment(s) is taken as a negative cash-flow, denoted ρ_N^{LT} in this paper. For the MGEM, the available LT decisions are linked to its fee: medium fee or low fee.

C. Short-Term Energy Management

The STEM is performed for the next day and gathers three global operation processes which are ordered as follows:

- Choosing the daily evolution of the commodity price;
- Applying industrial LM by modifying the consumption profiles of companies (LMO);
- Managing the energy exchanges inside the IMG or with the DN by the MGEM (microgrid operation or MGO).

1) Commodity Price Daily Profile: The first step is to define the electricity prices for both external and internal exchanges. In the current framework, electricity price for exchanges with the DN can be constant or variable over the considered day. For that purpose two Price Cases can be compared with the developed tool.

Price Case 1 (Constant Prices): The electricity prices are constant over the day for a whole year, for both internal (IMG prices) and external (outside prices) exchanges. Regarding the considered LT scenario (see Section II-A2), those prices are changed over the years. The initial price for exchanges with the DN is the mean one over all the available years of data [27] $\pi_{out,cst}$. The purchasing and selling prices outside the IMG (vectors $\Pi_{out,p}$ and $\Pi_{out,s}$, respectively) are therefore defined for each day as:

$$\Pi_{out,p} = \left[\pi_{out,p,1}, \ldots, \pi_{out,p,24}\right] \quad (2)$$

$$\forall h \in [1, \ldots, 24]: \quad \pi_{out,p,h} = \pi_{out,cst} \quad (3)$$

$$\Pi_{out,s} = \pi_r \times \Pi_{out,p} \quad (4)$$

where $0 < \pi_r < 1$. For peer-to-IMG exchanges, the IMG purchasing and selling prices ($\Pi_{in,p}$ and $\Pi_{in,s}$, respectively) practised by the MGEM are also constant and are defined as:

$$\Pi_{in,p} = \pi_{\%} \times \Pi_{out,p} \quad (5)$$

$$\Pi_{in,s} = \pi_r \times \Pi_{in,p} \quad (6)$$

where $0 < \pi_{\%} < 1$.

Price Case 2 (Variable Prices): In that case, a variability of the price over the day is considered (time-of-use variability). This variability is fixed, according to available prices data, for the exchanges with the DN (via an electricity supplier). To that end, several years of historical spotmarket data [27] are classified into 5 clusters of which the centroids are presented in Fig. 3.

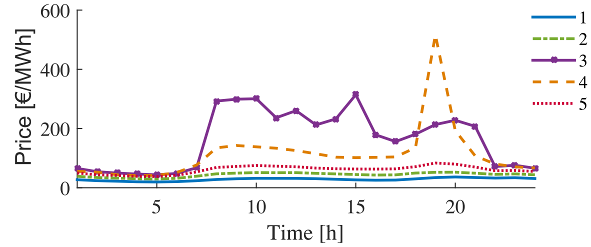

Fig. 3. Five centroids from the clustering of price data.

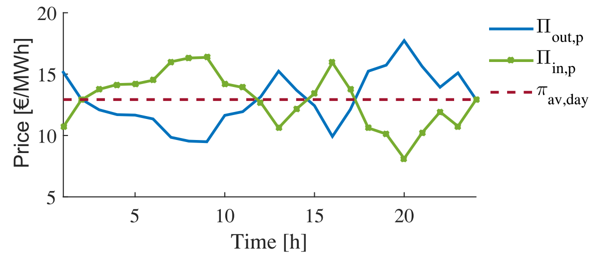

Fig. 4. Example of opposed prices inside and outside the IMG.

The clusters 1, 2 and 5 gather price profiles which are nearly constant with different levels. The cluster 3 is for days with a high commodity price and the cluster 4 represents the days with a price peak in the evenings. Those two last clusters occur only a few days per year. For each simulated day, a cluster is randomly chosen, taking into account its occurrence probability in the available data. A daily price profile included in this cluster is afterwards uniformly and randomly chosen as the deterministic and perfect forecast variable price profiles for the next-day (i.e., $\Pi_{out,p}$ and $\Pi_{out,s} = \pi_r \times \Pi_{out,p}$).

In that second case, the IMG prices can either follow the same trend as the outside prices, or be constant (in the same way than for the first case), or follow the opposite trend. Those three possibilities are considered in this work as available ST decisions for the MGEM in the STEM. For the two first ones, $\Pi_{in,p}$ is defined by (5). For the last one, $\Pi_{in,p}$ is defined by (7) and the constraint (1) has no longer to be always respected. Fig. 4 shows a $\Pi_{in,p}$ vector with an opposite trend than the corresponding $\Pi_{out,p}$ one. Note that $\Pi_{in,s}$ is always defined by (6).

$$\Pi_{in,p} = \pi_{\%} \times \left(\pi_{av,day} - \left(\Pi_{out,p} - \pi_{av,day}\right)\right) \quad (7)$$

$$\text{where:} \quad \pi_{av,day} = \frac{\sum_{h=1}^{h=24} \pi_{out,p,h}}{24}. \quad (8)$$

2) LMO: The developed LMO is inspired from [20] and [23]. The presented LM methodology is only valid for the industrial companies from Class 2 (i.e., with a daily bell curve during the working hours of the day and a low and/or constant base load during nights). The method is based on the fact that the load of an industrial company can usually be divided into two parts: the base load and the process load. The base load is the load which is not flexible and which can consequently not be shifted. The process load is the load linked to industrial activities. According to the company, these loads are more or less shiftable. For each hour h of a day, the load of a company

$N \in [2, \ldots, N_{tot}]$ can be expressed as:

$$l_{N,h} = l_{b,N,h} + l_{pr,N,h} \quad (9)$$

However, industrial processes have to be taken into account only during the working hours, e.g., between 6am and 6pm (13 hours). For each day and for each industrial company N, two vectors can therefore be defined:

$$L_{b,N} = \begin{bmatrix} l_{b,N,1} & \cdots & l_{b,N,13} \end{bmatrix} \quad (10)$$
$$L_{pr,N} = \begin{bmatrix} l_{pr,N,1} & \cdots & l_{pr,N,13} \end{bmatrix} \quad (11)$$

LM can only be processed on $L_{pr,N}$ (with some constraints) whereas $L_{b,N}$ cannot be changed. This means that $L_{pr,N}$ can be arranged in order to provide the desired load profile according to the consumer or prosumer status of the company.

In order to take into account the potential price variation over the period of application of LM, a LM price vector, Π_{LM}, is defined as the chosen price profile divided by its average, $\pi_{av,LM}$, over the considered time period.

$$\Pi_{LM} = \frac{\left[\pi_{out,p,6}, \ldots, \pi_{out,p,18}\right]}{\pi_{av,LM}} = \left[\pi_{LM,1}, \ldots, \pi_{LM,13}\right] \quad (12)$$

$$\text{where:} \quad \pi_{av,LM} = \frac{\sum_{h=6}^{h=18} \pi_{out,p,h}}{13} \quad (13)$$

This allows to give a weight to each hour (see (15) and (17)), according to the electricity market price.

For consumers: The peak of consumption represents a huge part of their electricity bill. LM is thus used to minimize the commodity price over a whole day by smoothing the consumption profile around the average consumption of the day $l_{av,N}$:

$$l_{av,N} = \frac{\sum_{h=6}^{h=18} l_{N,h}}{13} \quad (14)$$

The optimization problem resulting from this kind of LM can be written as a MILP problem. In (15), the bracketed part is the coefficient vector made of all the combinations of the hourly bases $l_{b,N,h}$ (fixed) and processes values $l_{pr,N,h'}$ (shifted). x is the integer vector with binary decisions to activate the process shiftable load at each hour $h \in [1 \quad \cdots \quad 13]$. Those vectors are therefore composed of the number of hours multiplied by the number of processes (i.e., 13×13) elements. The optimization is computed to find the combinations which fulfill at best the objective over the 13 hours. Each process is no longer necessarily attached to its initial hour of occurrence, i.e., h' can be equal or different from h.

$$\min_x \sum_{h=1}^{h=13} \left[\left|l_{b,N,h} + l_{pr,N,h'} - l_{av,N}\right| \times \pi_{LM,h}\right]^{\top} \times x \quad (15)$$

For prosumers: In order to make their PV installation more profitable, LM can be used to improve their self-consumption. This goal can also be expressed as decreasing the difference between their consumption and the generation P_N for the considered day:

$$P_N = \begin{bmatrix} p_{N,1} & \cdots & p_{N,13} \end{bmatrix} \quad (16)$$

In the same way than for the consumers, the MILP optimization problem resulting from LM for prosumers can be expressed by (17), with $h' \in [1 \quad \cdots \quad 13]$.

$$\min_x \sum_{h=1}^{h=13} \left[\left|l_{b,N,h} + l_{pr,N,h'} - p_{N,h}\right| \times \pi_{LM,h}\right]^{\top} \times x \quad (17)$$

For both optimization problems, the constraints are made so that each process can occur only once during the corresponding day with only one process to be operated at each hour. Those constraints allow to still have one process at each hour (as in the initial load profile) and to not overload some hours of the working day. Moreover, each day, the same processes have globally been realized. The habits of the company are therefore not drastically changed.

3) MGO: The microgrid operation is performed by the MGEM for each day. First of all, the prosumers self-consume a maximum of their own generation (with and without LM). After that first step, each stakeholder communicates its status of producer or consumer to the MGEM as well as the amount of electricity to sell $g_{N,h}$ or to purchase $\lambda_{N,h}$. Practically, three cases can be observed:

- If $p_{N,h} < l_{N,h}$: prosumer $N \equiv$ purchaser, $g_{N,h} = 0$ and $\lambda_{N,h} = l_{N,h} - p_{N,h}$;
- If $p_{N,h} > l_{N,h}$: prosumer $N \equiv$ seller, $g_{N,h} = p_{N,h} - l_{N,h}$ and $\lambda_{N,h} = 0$;
- If $p_{N,h} = l_{N,h}$: prosumer N is neutral, $g_{N,h} = \lambda_{N,h} = 0$.

The MGEM defines for each hour the total electricity to be sold and to be purchased by all industrial companies. For each hour h, the total load $L_{tot,h}$ and the total excess of generation $G_{tot,h}$ are defined as:

$$L_{tot,h} = \sum_{N=2}^{N=N_{tot}} \lambda_{N,h}, \quad G_{tot,h} = \sum_{N=2}^{N=N_{tot}} g_{N,h} \quad (18)$$

The next step is to define for each stakeholder $N = [2, \quad \cdots \quad N_{tot}]$ the quantity of electricity to buy or sell at each hour and at which price (inside or outside the IMG). For each of them, a ST hourly cash-flow $\Delta\rho^{ST}_{N,h}$ is increased by their hourly incomes and decreased by their hourly expenses defined according to the three following cases. Such a cash-flow is also defined for $N = 1$, i.e., for the MGEM, with the different fees linked to both roles of DSO and MGEM. For a neutral prosumer, given that there are no exchanges of electricity, its ST hourly cash-flow is equal to zero.

If $L_{tot,h} > G_{tot,h}$: all the generation is sold inside the IMG (peer-to-microgrid exchanges) at the IMG selling price $\pi_{in,s,h}$ (20). IMG consumers purchase a part of their electricity need $X_{N,h}$ (see (19)) at the IMG purchasing price $\pi_{in,p,h}$ proportionally against the total load covered by the total generation. The remaining electricity need comes from outside the IMG (through a supplier) and is purchased at the purchasing price $\pi_{out,p,h}$ (21). The MGEM earns a fee corresponding to the percentages of each price for each of those exchanges (respectively $g_{\%}$, $s_{\%}$ and $p_{\%}$ for the purchase outside the IMG, the selling and the purchase inside the IMG (22)):

$$X_{N,h} = \frac{G_{tot,h}}{L_{tot,h}} \times \lambda_{N,h} \quad (19)$$

If $N = seller$:

$$\Delta\rho_{N,h}^{ST} = g_{N,h} \times \pi_{in,s,h} - \pi_{in}^{met} - \pi_{out}^{met} \tag{20}$$

If $N = purchaser$:

$$\Delta\rho_{N,h}^{ST} = -X_{N,h} \times \pi_{in,p,h} - \left(\lambda_{N,h} - X_{N,h}\right) \times \pi_{out,p,h} - \pi_{in}^{met} - \pi_{out}^{met} \tag{21}$$

If $N = 1(MGEM)$:

$$\begin{aligned}\Delta\rho_{N,h}^{ST} = {} & g_{\%} \times \pi_{out,p,h} \times \sum_{N=2}^{N=N_{tot}} \left(\lambda_{N,h} - X_{N,h}\right) \\ & + s_{\%} \times \pi_{in,s,h} \times \sum_{N=2}^{N=N_{tot}} g_{N,h} \\ & + p_{\%} \times \pi_{in,p,h} \times \sum_{N=2}^{N=N_{tot}} X_{N,h} \\ & + (N_{tot} - 1) \times \left(\pi_{in}^{met} + \pi_{out}^{met}\right)\end{aligned} \tag{22}$$

If $L_{tot} < G_{tot}$: the load of each consumer can be fully covered by the total generation of the IMG. Consumers can purchase all their electricity needs at $\pi_{in,p,h}$ (24). The excess of generation of each prosumer, computed proportionally against the total consumption (23), is sold at a supplier at the selling price $\pi_{out,s,h}$ (25). The benefits for the MGEM are computed as above, taking into account the percentage $z_{\%}$ of the selling price outside of the IMG (26):

$$Z_{N,h} = \frac{L_{tot,h}}{G_{tot,h}} \times g_{N,h} \tag{23}$$

If $N = purchaser$:

$$\Delta\rho_{N,h}^{ST} = -\lambda_{N,h} \times \pi_{in,p,h} - \pi_{in}^{met} - \pi_{out}^{met} \tag{24}$$

If $N = seller$:

$$\Delta\rho_{N,h}^{ST} = Z_{N,h} \times \pi_{in,s,h} + \left(g_{N,h} - Z_{N,h}\right) \times \pi_{out,s,h} - \pi_{in}^{met} - \pi_{out}^{met} \tag{25}$$

If $N = 1(MGEM)$:

$$\begin{aligned}\Delta\rho_{N,h}^{ST} = {} & z_{\%} \times \pi_{out,s,h} \times \sum_{N=2}^{N=N_{tot}} \left(g_{N,h} - Z_{N,h}\right) \\ & + s_{\%} \times \pi_{in,s,h} \times \sum_{N=2}^{N=N_{tot}} Z_{N,h} \\ & + p_{\%} \times \pi_{in,p,h} \times \sum_{N=2}^{N=N_{tot}} \lambda_{N,h} \\ & + (N_{tot} - 1) \times \left(\pi_{in}^{met} + \pi_{out}^{met}\right)\end{aligned} \tag{26}$$

If $L_{tot} = G_{tot}$: the load of all the consumers is covered by the total generation of the IMG and can be purchased at the microgrid price $\pi_{in,p,h}$ (27). Obviously, each producer can also sell its excess of electricity at the microgrid price $\pi_{in,s,h}$ (28). The manager cash-flow is computed by the earnings linked to internal exchanges (see (29)).

If $N = purchaser$:

$$\Delta\rho_{N,h}^{ST} = -\lambda_{N,h} \times \pi_{in,p,h} - \pi_{in}^{met} - \pi_{out}^{met} \tag{27}$$

If $N = seller$:

$$\Delta\rho_{N,h}^{ST} = g_{N,h} \times \pi_{in,s,h} - \pi_{in}^{met} - \pi_{out}^{met} \tag{28}$$

If $N = 1(MGEM)$:

$$\begin{aligned}\Delta\rho_{N,h}^{ST} = {} & s_{\%} \times \pi_{in,s,h} \times \sum_{N=2}^{N=N_{tot}} g_{N,h} \\ & + p_{\%} \times \pi_{in,p,h} \times \sum_{N=2}^{N=N_{tot}} \lambda_{N,h} \\ & + (N_{tot} - 1) \times \left(\pi_{in}^{met} + \pi_{out}^{met}\right).\end{aligned} \tag{29}$$

D. Objective Function Definition

After the definition of the different expenses and incomes for each stakeholder $N \in [1, \ldots, N_{tot}]$ linked to the LT investments ρ_N^{LT} and to the ST management, the cost objective function of the planning problem, taking into account the actualisation of the short-term cash-flow by a discount rate r, can be easily written as:

$$NPV_N = \rho_N^{LT} + \rho_{N,Y_{tot}\times 365}^{ST} \tag{30}$$

with:

$$\rho_{N,Y_{tot}\times 365}^{ST} = \rho_{N,t}^{ST} \quad when \quad Y = Y_{tot}, d = 365 \tag{31}$$

where Y_{tot} is the number of years of planning ($Y_{tot} = 20$), d represents the day of a year Y and $\rho_{N,t}^{ST}$ is the short-term cash-flow for the player N, accumulated until day $t = d + (Y - 1) \times 365$:

If $N = purchaser\ or\ seller$:

$$\rho_{N,t}^{ST} = \rho_{N,t-1}^{ST} + \left[\sum_{h=1}^{h=24} \Delta\rho_{N,h}^{ST} - l_N^{peak} \times \left(\pi_{d,p}^{peak} + \pi_{t,p}^{peak} + \pi_{in,p}^{peak}\right)\right] \Big/ (1 + r)^Y \tag{32}$$

If $N = 1(MGEM)$:

$$\rho_{N,t}^{ST} = \rho_{N,t-1}^{ST} \left[\sum_{h=1}^{h=24} \Delta\rho_{N,h}^{ST} + \sum_{N=2}^{N=N_{tot}} + \sum_{N=2}^{N=N_{tot}} l_N^{peak} \times \left(\pi_{d,p}^{peak} + \pi_{in,p}^{peak}\right)\right] \Big/ (1 + r)^Y \tag{33}$$

In (32) and (33), l_N^{peak} represents the responsibility of the prosumer N in the global IMG peak consumption. $\pi_{d,p}^{peak}$, $\pi_{t,p}^{peak}$ and $\pi_{in,p}^{peak}$ are, respectively, the peak part of the electricity distribution, transmission and IMG purchasing costs.

III. Solving Methodology

Another difficulty of this particular IMG planning process is to consider the different stakeholders. For this purpose, Game Theory is used to take into account the objectives of those different stakeholders.

A. Game Theory

Game Theory is a concept which models the interactions between some agents in order to take decisions that fulfill their own objectives in the best way. In the proposed tool, Game Theory is used in order to take decisions about the long-term investments as well as the short-term operational ones. This application is more detailed in this section, after exposing some definitions.

1) Definitions: A normal game with N_{tot}-players is defined by [28]:

- A set of actions $A_i = (a_{i1}, \ldots, a_{im_i})$ for each player $i = 1, \ldots, N_{tot}$ (with m_i the number of actions available for that player). A profile of actions is defined as $a = (a_1, \ldots, a_{N_{tot}}) \in A = A_1 \times \cdots \times A_{N_{tot}}$ where, e.g., a_1 denotes a particular action for the first player among its set of actions A_1.
- A payoff function $u_i : A_1 \times \cdots \times A_{N_{tot}} \rightarrow \Re$ which represents the preferences of the player i for its action in the considered profile of actions. At each profile of actions a is attached a payoff function $u = (u_1, \ldots, u_{N_{tot}})$. For a player i, if the payoff attached to action a_{i1} is higher than the payoff attached to action a_{i2}, this means that he prefers action a_{i1}.

Game Theory is based on the theory of the rational choice which means that a player will choose an action which is at least as good as the other available actions. The goal of Game Theory is then to find, among all the possibilities of actions profiles, the one which will best satisfy the N_{tot} players. In order to find this solution, the computation of a Nash equilibrium can be performed. This is a solving concept in which each player tries to maximise its own payoff given the chosen actions of the other players. The equilibrium is not necessarily the optimal solution for each one but is such that, if anyone deviates from it, the risk of weakening the global solution would increase. Mathematically, the Nash equilibrium can be expressed as follows [28]: the profile of actions a^* is a Nash equilibrium if, for each player i and for each action of the player i, a^* is at least as good, according to the preferences of the player i, as the profile (a_i, a^*_{-i}) in which the player i chooses a_i (in the profile a) and all the other players choose the profile a^*:

$$u_i\big(a^*\big) \geq u_i\big(a_i, a^*_{-i}\big). \tag{34}$$

2) Extensive Games: There exists a lot of categories of games in [28]. They take into account the possibility of making individual or grouped decisions, the knowledge (or not) of the other players choices, the simultaneity or the succession of the decision-making of all the players, the unique or probabilistic nature of the solution, etc. Among all the categories, one is called the non-cooperative extensive game with imperfect information. This kind of game has been chosen in order to avoid inter-connections between the industrial companies and to respect the confidentiality of the information (only communication with the MGEM). Its main characteristic is the possibility to describe the succession in the decision-making process of the N_{tot} players, which is then presented by a tree structure (Fig. 5). An extensive game is defined by [28]:

- A finite set of nodes η which forms the tree structure including the set τ of terminal nodes. At each node (except those within τ) is attached the player who can choose an action;
- A set of payoff functions u_i:$\tau \rightarrow \Re$ assigning payoff for the player i at each terminal node.

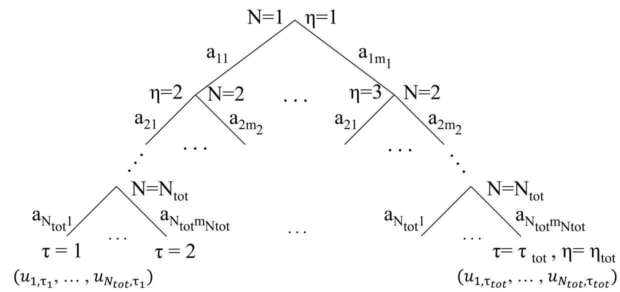

Fig. 5. Representation of an extensive game.

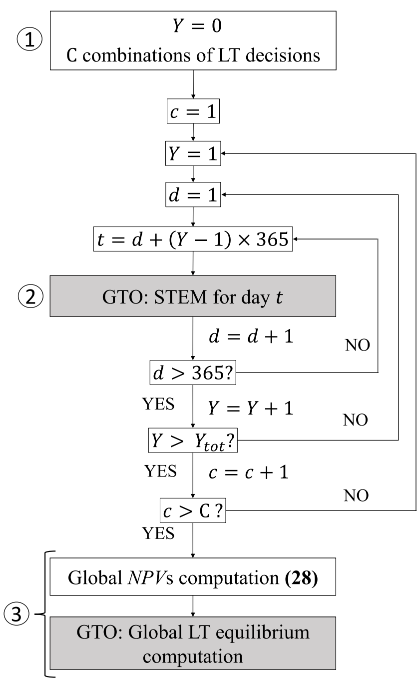

Fig. 6. Game Theoretical Methodology of the IMG planning tool.

The particularity of this kind of game is the possibility of switching to a Normal-Form game in order to compute a Nash Equilibrium, as described above.

B. Application of Game Theory to the Planning Process

The originality of the developed planning tool is to use Game Theory for the two levels of the decision-making process. For both levels, the players are the stakeholders of the IMG (including the DSO as MGEM), their actions consist in their decisions in order to fulfill their own objective, and the payoff functions are the cash-flows linked to those decisions. The game theoretical methodology of the planning tool is presented in Fig. 6, and the three main stages are described in this section.

1) Combination of LT Decisions: At the initial year, a first tree structure is established in order to clearly see the C possible combinations of investment decisions: invest in a PV installation or invest is a ESS for the prosumers/consumer and different fees for the MGEM (see Section II-C3). At each terminal node τ_c with $c \in [1, \ldots, C]$ of this tree, a payoff function is attached considering the payoff of each stakeholder N. This payoff is actually the long-term component of the cost objective function ρ_N^{LT} that will be now denoted ρ_{N,τ_c}^{LT} in order to take into account the considered terminal node. Each terminal node τ_c is then characterised by:

$$\left(u_1(\tau_c), \ldots, u_{N_{tot}}(\tau_c)\right) = \left(\rho_{1,\tau_c}^{LT}, \ldots, \rho_{N_{tot},\tau_c}^{LT}\right). \quad (35)$$

2) GTO for the STEM: For each day, a game is constructed according to those actions:

- For the MGEM: electricity pricing inside the IMG (IMG prices with the same variation than prices outside the IMG, constant or with the opposite variation compared to prices outside the IMG);
- For the companies from class 2: LMO is performed and their decisions are to apply LM or not;
- For the other companies: no ST decisions.

The MGO (Section II-C3) is performed for each combination of ST actions. Each stakeholder N is associated with its cumulative short-term cash-flow $\rho_{N,t}^{ST}$ for each terminal node τ_j, now denoted ρ_{N,t,τ_j}^{ST} to distinguish each node. Each terminal node of this daily tree is characterised by:

$$\left(u_1(\tau_j), \ldots, u_{N_{tot}}(\tau_j)\right) = \left(\rho_{1,t,\tau_j}^{ST}, \ldots, \rho_{N_{tot},t,\tau_j}^{ST}\right) \quad (36)$$

Then, the Nash Equilibrium is searched in order to define which stakeholder has to do LM and which kind of pricing scheme the MGEM has to apply. The ST cash-flow of the selected equilibrium is the initial value for the next day in order to increment the payoff functions. If there is no found Nash Equilibrium, the considered cash-flow is the first one, i.e., the one without LM and with same price variation than DN price.

3) Global NPVs and LT Equilibrium Computation: At the end of the $365 \times Y_{tot}$ days, a final cumulated short-term cash-flow $\rho_{N,365\times Y_{tot}}^{ST}$ is obtained for each stakeholder N. This term is added to each long-term cash-flow ρ_{N,τ_c}^{LT} to constitute a NPV (see Eq. (30)) at each terminal node $\tau_c \in [\tau_1, \ldots, \tau_C]$, now denoted NPV_{N,τ_c}. Each combination of actions c from the step 1 is now attached to:

$$\left(u_1(\tau_c), \ldots, u_{N_{tot}}(\tau_c)\right) = \left(NPV_{1,\tau_c}, \ldots, NPV_{N_{tot},\tau_c}\right) \quad (37)$$

An equilibrium [28] is then computed in order to determine the long-term policy to adopt in order to get a global socio-economical welfare inside the microgrid while satisfying at best each stakeholder and taking into account the proper ST management.

IV. Application of the Tool on a Virtual Industrial Microgrid

The considered virtual microgrid is composed of 4 stakeholders: the DSO (= MGEM), 2 consumers (P1 and P2) and 1 prosumer (P3). The microgrid is connected to the 10.5 kV DN. The long-term decisions available for the consumers are to invest in a PV installation (PV) or to do nothing (No). The prosumers can choose to invest in an ESS or to do nothing (No). For the MGEM, the LT decisions are to apply either a medium fee or a low fee. Regarding the STEM, only P1 and P3 have consumption profiles which allow doing LM. The uncertainty of the consumptions and prices LT evolutions are taken into account through several scenarios (S) defined as follows:

- Global consumption remains constant (S_1):
  - $S_{1,1}$: Prices are unchanged over the planning period;
  - $S_{1,2}$: Prices increase by 2% each year;
  - $S_{1,3}$: Prices decrease by 2% each year.
- Global consumption increases by 2% each year (S_2):
  - $S_{2,1}$: Prices are unchanged over the planning period;
  - $S_{2,2}$: Prices increase by 2% each year;
  - $S_{2,3}$: Prices decrease by 2% each year.
- Global consumption decreases by 2% each year (S_3):
  - $S_{3,1}$: Prices are unchanged over the planning period;
  - $S_{3,2}$: Prices increase by 2% each year;
  - $S_{3,3}$: Prices decrease by 2% each year.

A. Analysis of the LT Decisions and the Global NPV

For all scenarios, the found equilibrium corresponds to the combination of applying a medium fee for the MGEM, investing in a PV installation for P1 and P2 and doing nothing for P3. Four NPVs are computed over the 20 years of planning in order to analyze and discuss the results:

- NPV_0 is the NPV if there are no investments and no IMG (i.e., the current situation);
- NPV_{inv} is the NPV if only investments are realized (without microgrid and without LM);
- NPV_{noLM} is the NPV with investments and the IMG framework, but without LM;
- NPV_{img} is the NPV with investments, the IMG framework and the possibility of performing LM.

All the scenarios have been simulated for the two Price Cases described in Section II-C1 (constant or variable prices). The whole simulation for one scenario over 20 years takes about 92.5 min with an Intel Core i7-6700 HQ, 2.6 GHZ, 16 Go random access memory computer.

The first analysis consists in comparing the situations integrating investments with the current one according to three cases:

1. Comparison between the current situation and the situation with only investments:
$$\%_{NPV,N} = \frac{\left(NPV_{inv,N} - NPV_{0,N}\right)}{NPV_{0,N}}$$
2. Comparison between the current situation and the situation with investments and IMG framework:
$$\%_{NPV,N} = \frac{\left(NPV_{noLM,N} - NPV_{0,N}\right)}{NPV_{0,N}}$$
3. Comparison between the current situation and the situation with investments, IMG framework and LM:
$$\%_{NPV,N} = \frac{\left(NPV_{img,N} - NPV_{0,N}\right)}{NPV_{0,N}}$$

As the MGEM NPVs are positives (see Section II-C3), a negative $\%_{NPV,N}$ represents a loss and a positive one means an earning. For P1, P2 and P3, the NPVs are negatives and, therefore, a lower $\%_{NPV,N}$ represents a more important saving. Fig. 7 presents results corresponding to the variable prices (Price Case 2); given the used prices data, results with constant prices lead to similar conclusions.

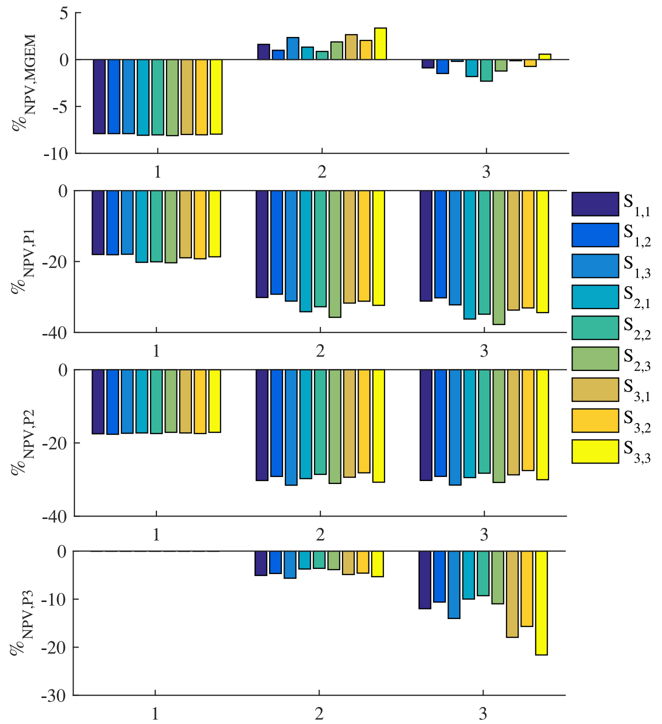

Fig. 7. Percentages $\%_{NPV,N}$ for the MGEM, P1, P2 and P3, for all scenarios.

Fig. 7 shows that, if there is no IMG and only investments, the DSO would lose money compared to the current situation. Indeed, when consumers invest in PV, exchanges with the DN are decreased and the DSO loses money since the distribution grid energy component of the bill is decreased accordingly. With an IMG managed by the DSO, those losses are reduced or even become benefits thanks to its earnings as MGEM. Indeed, in case 2 (without LM), the losses are all changed in benefits. This is not the case with LM (case 3), given that LM leads to a decrease of the exchanges inside the IMG (improving the self-consumption via $LM_{prosumer}$) and to a decrease of the peak of consumption (peak shaving via $LM_{consumer}$). However, the remaining losses are widely reduced compared to the first case.

For the prosumers P1 and P2, a PV installation is the appropriate choice in order to reduce their expenses, even without IMG. The PV installation allows them to reduce their quantity of electricity to be bought. Moreover, their benefits are increased with the IMG framework, including the STEM. Indeed, for P1, the savings are increased by 11 to 15% with the IMG and for P2 by 10 to 14 %, according to the scenario. This is also thanks to the STEM that P3 makes savings (between 3.6 and 5.6%), even though its decision is to do nothing. Note that the decision to invest in an ESS for P3 is never taken because such an investment is still too expensive, even with the proposed IMG framework.

Regarding the influence of LM, the conclusions are not the same for P1 and P3. Indeed, for P1, there is no significant difference between case 2 and case 3 while the savings of P3 are more than doubled or tripled according to the considered scenario (increase of the savings between 6 and 16%). In order

TABLE I
OCCURRENCE OF LM FOR P1 AND P3 IN ALL SCENARIOS

	P1 - Fix [%]	P1 -Var [%]	P3 - Fix [%]	P3 - Var [%]
S_1	78.65	74.56	77.52	76.25
S_2	79.12	75.88	76.88	75.73
S_3	78.96	75.63	77.75	77.12

to further observe the influence of LM, Table I gathers the occurrence of LM for P1 and P3 over the 20 years of planning, i.e., the number of days, among the $5 \times 52 \times 20$ computed working days, during which LM is the decision found with the STEM. This table shows that the choice of performing LM remains more or less constant, whatever the considered scenario. The occurrence of LM is important for both P1 and P3. The economical benefits for P3 have been demonstrated thanks to Fig. 7 while it seems not as economically interesting for P1 compared to its occurrence. This can be explained by the fact that P1 has a high base load. Consequently, fitting consumption and generation does not have any sense during less sunny periods of the year.

1) Time of Return on Investments: Besides reducing the global expenses over the 20 years horizon, the IMG also allows a reduction of the time of return on investment. The development of the IMG framework with LM allows, in average, a decrease of about 29.3% of the time of return on investment for P1 and 26.1% for P2. If the LMO is ignored, this value is reduced to 26.2% for P1 and slightly increased to 26.5% for P2. Indeed, even if P2 is not performing LM, the amount of electricity exchanged inside the IMG increases when no LM is practised inside the IMG, allowing P2 to purchase more electricity at the interesting IMG price.

2) Pricing Scheme Inside the IMG: In Price Case 2, with variable DN prices, the MGEM also has the possibility to apply different ST pricing schemes inside the IMG. This section shows the occurrence of each kind of pricing scheme over the 7300 days of planning for the simulations with and without the LMO:

- *Same trend than DN prices:* According to the scenario, this first case is adopted between 3187 to 3576 days when LM is performed, which corresponds to about 47% of the time. If LMO is not applied, this case is chosen between 3510 and 3838 days, i.e., its occurrence increases to 51%;
- *Constant price:* This second case is adopted between 1599 and 1798 days (i.e., 23% of the time) with LM and between 1638 and 1915 days (i.e., 24% of the time) without LM;
- *Opposite trend than DN prices:* This last case is chosen between 2125 and 2350 (i.e., 30% of the time) when LM is applied, while only used between 1689 and 1990 days (25%) without LM.

This means that applying prices with the same trend than the DN price is the most common choice while the occurrences of the other kinds of pricing are quite similar.

B. Analysis of the Power Exchanges

In this section, the operation of the IMG as a whole is analyzed through different indices inspired from [29], which

TABLE II
INTERNAL AND EXTERNAL INDICES FOR VARIABLE PRICES (PRICE CASE 2) AND WITH LM

	TIC $[kW]$	REP [pu]	IEP [pu]	IEE $[GWh]$
S_1	830.82	0.3299	0.2201	1.631
S_2	897.42	0.3187	0.2241	1.983
S_3	811.25	0.3545	0.2258	1.414
	PP [pu]	TEP $[GWh]$	SP [pu]	TES $[GWh]$
S_1	0.8751	42.70	0.1249	3.556
S_2	0.8820	48.27	0.1180	3.602
S_3	0.8545	38.37	0.1455	4.200

are computed over the Y_{tot} years of planning. The top part of Table II summarizes the installations and exchanges inside the IMG. The internal indices are the Total Installed Capacity (*TIC*), the Renewable Energy Penetration (*REP*, computed as the ratio between the total *kWh* renewable energy produced and the total *kWh* electricity demand), the Internal Exchanges Probability (*IEP*, computed as the ratio between the total hours of internal exchanges and the total hours of operation $8760 \times Y_{tot}$) and the Internal Energy Exchanges (*IEE*). The lower part of Table II allows the analysis of the exchanges between the IMG and the DN. The external indices are the Purchase Probability to the DN (*PP*, computed as the ratio between the sum of hours when the IMG purchases energy from the DN and the total grid-connected hours), the Total Energy Purchased (*TEP*) from the DN, the Selling Probability to the DN (*SP*, computed as the ratio between the sum of hours when the IMG sales energy to the DN and the total grid-connected hours) and the Total Energy Sold (*TES*) to the DN. Table II presents those indices for S_1, S_2 and S_3 (as the LT electricity prices evolutions do not change significantly their values).

As the sizing of the PV installation is adapted to the future evolution of the consumption, the *TIC* is adapted for each scenario. This allows the *REP* to be more or less constant, even if it is slightly lower for S_2 and higher for S_3. Given the fact that generation and consumption are both higher for S_2, the *IEE* is also higher (even if the *TEP* remains almost constant). Regarding the *PP*, its higher value for S_2 is also directly linked to the lowest *REP*. Indeed, there is more energy to purchase in order to cover all the consumption. On the other hand, the *SP* is lower, which means that the amount of electricity self-consumed is higher. The argumentation is the opposite one for S_3.

In order to further analyse the exchanges, the self-consumption rates have also been computed (see Table III). For P1 and P3, their analysis follows the previous observations: whatever the considered scenario is, the self-consumption rate remains almost constant for P1 and the one of P3 increases between 4 and 6 % with LM (showing the benefit of LM only for P3). The self-consumption rates are the lowest for the scenarios S_3, which is congruent with the fact that *SP* and *TES* are also higher in Table II. Indeed, if the self-consumption is lower inside the IMG, more electricity is sold to the DN.

C. Technical Analysis

Each day, a load flow is performed a posteriori to check the voltage of the planned day in order to technically permit the selected decisions. Indeed, this step is very important given the fact that the objective function and the computed equilibria are only based on economics parameters. This load flow allows to observe the nominal voltage at each node as well as the power flows. In all the simulated scenarios, the voltage of 10.5kV remains within the limit of -10% and $+10\%$, and so the proper operation of the IMG is ensured.

TABLE III
SELF-CONSUMPTION RATES FOR P1, P2 AND P3

	Without LM			With LM		
	P1	P2	P3	P1	P2	P3
S_1	89.57	62.15	74.03	90.56	62.15	79.17
S_2	86.77	60.46	77.39	87.54	60.46	81.37
S_3	86.98	60.46	69.55	87.86	60.46	75.14

V. CONCLUSION

This paper describes a tool for the long-term planning of IMGs made of industrial consumers, prosumers and the DSO, which takes into account the microgrid Short-Term Energy Management on a daily basis. The DSO assumes here the role of MGEM. The goal of this tool is to give guidelines to the different stakeholders about the long-term investments to realize (RES and ESS) as well as the short-term policy to adopt (peer-to-microgrid vs external exchanges and LM vs no LM). The proposed methodology couples two game theoretical frameworks in order to manage the different time horizons of the decision-making process. The short-term (i.e., daily) evolution of prices has been investigated through two pricing schemes, namely constant and variable prices. More particularly, different correlation levels between the prices pertaining to internal exchanges within the IMG and prices related to external exchanges have been considered. Furthermore, long-term (i.e., yearly) uncertainties concerning the evolution of prices and consumption have been studied through the simulation of nine long-term scenarios.

The results have shown that, for consumers who invest in a PV installation, the profit is increased and the time of return on investment is decreased thanks to the IMG framework (including LM). Indeed, the operation inside an IMG allows the prosumers to take more advantage of their generation. For the DSO acting as the MGEM, it is shown that the expected financial losses linked to the decrease of external exchanges via the DN (and thus to a decrease of the grid component of the companies electricity bills) are almost entirely compensated by its fees for its new role. It is also shown that the best compromise is obtained in most cases when prices for internal exchanges follow the same trend than the prices for external exchanges. Finally, the analysis of some exchanges indices and of the prosumers self-consumption rates have confirmed the previous results.

There are many perspectives to this tool: non-perfect forecasts and deviations from the scheduled behaviour should be considered in the STEM. Furthermore, this tool has been tested on a small virtual industrial microgrid, and the LMO is realized independently for each stakeholder. One interesting perspective of this tool would be to develop a cooperative or a centralized LMO inside a larger industrial microgrid.

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