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Long-term planning of connected industrial microgrids

Towards tractable decisions by game theory and energy exchanges management

PhD Thesis

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Contents

Nomenclature

Acronyms

CLM	Centralised Load Management
DLM	Decentralised Load Management
DN	Distribution Network
DSO	Distribution System Operator
ESS	Energy Storage System
GC	Green Certificate
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 System
ROI	Return On Investment
RR	Return rate
SCR	Self-Consumption Rate
SOC	State Of Charge
SP	Sale Probability
ST	Short-Term
$STEM$	Short-Term Energy Management
TEP	Total Energy Purchased
TES	Total Energy Sold
TIC	Total Installed Capacity

Price variables

$\Pi_{out,p}$	Vector of Purchasing Price outside the IMG
$\Pi_{out,s}$	Vector of Selling Price outside the IMG
$\Pi_{in,p}$	Vector of IMG Purchasing Price
$\Pi_{in,s}$	Vector of IMG Selling Price
$\pi_{out,p,h}$	Hourly Purchasing Price outside the IMG
$\pi_{out,s,h}$	Hourly Selling Price outside the IMG
$\pi_{in,p,h}$	Hourly IMG Purchasing Price
$\pi_{in,s,h}$	Hourly IMG Selling Price
$\pi_{out,cst}$	Mean Purchasing Price outside the
$r_{out/in}$	Ratio between purchasing and selling prices
$r_{p/s}$	Ratio between IMG and DN purchasing prices
r_P	Peak pricing ratio
r_{in}^{dso}	DSO fee ratio inside the IMG
r_{in}^{fee}	MGEM fee ratio inside the IMG
$\pi_{av,LM}$	Price Average over the LM period
$\pi_{av,day}$	Price Average over the day
Π_{LM}	Purchasing Price Weight Vector
$\pi_{LM,h}$	Hourly Weight of Purchasing Price
π_{in}^{met}	IMG Metering Price
π_{out}^{met}	DN Metering Price
$\pi_{out,p}^{peak,t}$	Peak part of the transmission purchasing cost
$\pi_{out,p}^{peak,d}$	Peak part of the distribution purchasing cost
$\pi_{in,p}^{peak}$	Peak part of the IMG purchasing cost
$\pi_{out,p}^{fee,t}$	Energy part of the transmission purchasing cost
$\pi_{out,p}^{fee,d}$	Energy part of the distribution purchasing cost
$\pi_{out,s}^{fee,d}$	Energy part of the distribution selling cost
$\pi_{out,p}^{new}$	Renewable fee part of the distribution purchasing cost
$\pi_{out,p}^{taxes}$	Taxes part of the distribution purchasing cost
π^{GC}	Green certificate cost
$\pi_{in,p}^{fee}$	MGEM fee of the IMG purchasing cost
$\pi_{in,s}^{fee}$	MGEM fee of the IMG selling cost
$\pi_{in,p}^{dso}$	DSO fee of the IMG purchasing cost

Cash-flow variables

r	Discount Rate
$\Delta\rho_{s,h}^{ST}$	ST Cash-flow of stakeholder s for hour h
$\rho_{s,t}^{ST}$	Accumulated ST Cash-flow of stakeholder s
ρ_{s}^{LT}	LT Cash-flow of stakeholder s
η_s	NPV of the stakeholder s with IMG
$\eta_{0,s}$	NPV of the stakeholder s without investments and IMG
$\eta_{inv,s}$	NPV of the stakeholder s with investments and without IMG
$\eta_{noLM,s}$	NPV of the stakeholder s with IMG but no LM (first tool)
$\rho_{LM,s}^{1y}$	NPV after 1 year with LM of the stakeholder s with IMG
$\%_{\eta_s}$	Percentage NPV of saving/loss of s
$\%_s^{1y}$	Percentage of NPV saving/loss after 1 year for stakeholder s
$\rho_{d,s}$	Mean daily cash-flow of s for day d
ρ_s	Extended mean daily cash-flow of s
ρ_s^{1y}	Extended mean daily cash-flow over one year of s

Load and generation variables

$l_{s,h}$	Hourly Load of stakeholder s
$l_{b,s,h}$	Hourly Base Load of stakeholder s
$l_{pr,s,h}$	Hourly Process Load of stakeholder s
$L_{b,s}$	Vector of Base Loads of stakeholder s
$L_{pr,s}$	Vector of Process Loads of stakeholder s
$l_{av,s}$	Load Average over the LM period of stakeholder s
P_s	Production Vector of stakeholder s
$p_{s,h}$	Hourly production of stakeholder s
$\lambda_{s,h}$	Hourly remaining load of stakeholder s
$g_{s,h}$	Hourly remaining production of stakeholder s
$L_{tot,h}$	Total remaining load of hour h
$G_{tot,h}$	Total remaining production of hour h
$X_{s,h}$	Load of s covered by the generation inside the IMG at hour h
$X_{s,h}$	Energy purchased inside the IMG by s at hour h
$Z_{s,h}$	Energy sold via the DN by s at hour h
l_s^{peak}	Load peak of s in the IMG
$l_{s,LM}^{peak}$	Load peak of s in the IMG with LM
l_{IMG}^{peak}	Global load peak of the IMG
$\%_{d,s}$	Occurrence percentage of LM for stakeholder s
$RES_{\%,s}$	Weight of the RES of s among the global installation
$ESS_{\%,s}$	Weight of the ESS of s among the global installation
W_s	Weight of the load peak of s among the global IMG load peak

Other variables

S	Number of stakeholders
C	Number of companies in the IMG
J	Number of ST combinations of decisions
Y_{tot}	Number of years of planning
N_{LT}	Number of terminal nodes of the LT game
A_{max}	Maximum amount of investments inside the IMG
Ψ_z	LT scenarios with $z = 1, ..., 9$
τ	Terminal node of an extensive game
I_d	Number of iterations without stratification
$I_{strat,d}$	Number of iterations with stratification
$I_{simu,d}$	Number of iterations in the final tool

Introduction, motivation and objectives

Since the liberalisation of the electricity market and the massive proliferation of the Renewable Energy Systems (RESs) in the electricity grid, a change of paradigm has occurred in the electricity field. This change has led to different challenges, technical as well as economical, environmental and social.

The main challenge is to develop a greener generation fleet to respond to the need of decarbonisation of the planet while stopping the use of nuclear energy for safety reasons. Therefore, it seems that a proper solution is to use sources of energy that are renewable such as the sun or the wind. For that purpose, the development of essentially PhotoVoltaic (PV) and Wind Turbine (WT) installations has been promoted during the last years by two ways. On the one hand, the existing producer companies invest in large fleets of PV and WT, and, on the other hand, the residential, commercial or industrial consumers invest in small decentralised installations.

However, the massive development of such RESs leads to two major issues: the first one is their decentralisation. They are developed all over the existing electricity grid, leading to bidirectional power flows on the distribution network which was not initially designed for that kind of exchanges. The second one is linked to their intermittent operation, depending on the weather and inducing uncertain stresses on the electricity system.

Such RESs have therefore to be developed in parallel with Energy Storage Systems (ESSs) and/or with a smart management of the electricity exchanges. Indeed, the consumers (residential, commercial and industrial) are not passive anymore. If they invest in RESs and/or ESSs, they become prosumers. For them, as well as for those who remain consumers, their loads have to be smartly adapted to the intermittent generation. All those changes have led to the concept of *smart grid*. The smart grid includes the RESs and the ESSs, with a communication channel in parallel which allows the proper information sharing between the producers, the consumers and the prosumers.

However, all those investments and changes lead to financial and social issues. Indeed, since a few years, the global electricity price has increased. Hence, the performances of such installations as well as their feasibility and profitability have to be demonstrated to be accepted by the residential and the industrial society, over the long-term time horizon.

One way to take advantage at best of these elements is to form *microgrids*. The notion of microgrid is often used but is sometimes quite confusing. Indeed, on the one hand, a single company or a house with its own RES, and potentially ESS, can be called microgrid in the literature. On the other hand, a group of residential houses or industrial companies that are connected to the Distribution Network (DN) by one or several connecting node(s) can also be called microgrid. **This thesis focuses on the microgrid in the industrial field including several companies.**

As the time of return on investments in RESs and ESSs is often over several years, some companies may be reluctant to invest in such installations. Without being part of a microgrid, this time only depends on their own self-consumption and energy management. With a microgrid, the investment is performed by the company but the energy management is taken over by a microgrid manager. Therefore, in order to increase the self-consumption rate and decrease the time of return on investment, such companies could take advantage of the complementarity of their load profiles inside a so-called Industrial MicroGrid (IMG).

However, to our knowledge at the beginning of this thesis, three main issues were not clear in the elaboration of such a microgrid. The first issue concerns the way of long-term planning such a microgrid by taking into account all the stakeholders, in order to promote the concept and to convince the companies to be part of it. The second point is related to the management of the microgrid. Indeed, the role of manager has to be properly defined regarding its possible actions and decisions as well as its knowledge about the other participants (including the confidentiality aspects). The last but not least issue is related to the regulatory framework. In the current one, the rules of electricity exchanges are well defined and it is clearly forbidden to share electricity in another way. Therefore, the concept of microgrid has to put these rules into question by developing a specific internal regulatory framework.

The purpose of this thesis is therefore to clarify and study the different challenges pertaining to microgrids. More particularly, the main objective is to develop a tool for industrial microgrids planning in order to promote the development of such structures and to provide advices about a new regulatory framework for microgrids.

The development of such a planning tool has to face several challenges. The first main difficulty is to consider, at the same level, all the stakeholders of the microgrid, including the distribution system operator and the owner of the industrial area. Indeed, each one has to be taken into account individually in order to consider his respective objectives and possible actions. This is possible through the use of game theory as discussed further in this thesis.

The second main issue is linked to the fact that the proper long-term planning of microgrids has also to consider a proper energy management at a short-term time horizon. The latter has to be accurate and fast enough to be handled over the long-term planning horizon. Indeed, the planning horizon is 20 years, thus bringing to 7300 simulated days. Therefore, the reduction of the execution time of the complete planning tool is also an important element of the research.

Moreover, in order to develop a new microgrid, some long-term uncertainties have to be considered as well as different investment configurations. The tool developed in this thesis has to handle a maximum of long-term possibilities through long-term pricing plans and long-term scenarios for the load and price profiles evolutions.

Finally, the notions of smart grids and microgrids also include some new energy management methodologies. Indeed, in order to adapt the electricity consumption to the intermittent generation, the principle of Load Management (LM) is often used to shift the flexible loads towards hours with an higher generation. This principle will also be studied in the tool developed in this thesis.

Content

The remaining of this thesis is composed of five main chapters:

- The first one is dedicated to a detailed description of the electricity system evolution, in order to properly introduce the notions of smart grid and microgrid. Then, a deep state of the art regarding the planning, the operation and the components of microgrids is presented, as well as the originalities of the principles developed in this thesis;

- In the second chapter, the general methodologies and principles set up for the tool developed in this thesis are presented. They concern the consideration of all stakeholders on equal terms (thanks to game theory), the new microgrid regulatory framework (including the microgrid pricing scheme) and the management of the electricity exchanges inside the microgrid (including load management) and with the distribution network. A two time horizons decision making process is presented in order to consider both the long-term decisions of investments and the short-term decisions regarding the IMG pricing and the LM;

- The third chapter is a concrete application of the previously presented principles through a first version of the planning tool devoted to small microgrids. The complete principle is presented as well as some simulation results. This chapter ends up by presenting the limits of this tool regarding its complexity and its simulation time. Indeed, the size of the games increases exponentially with the number of stakeholders and actions. Moreover, the execution of the LM process each day is time consuming;

- The fourth chapter gathers all the potential solutions studied to counter the limits and the weaknesses of the first version of the planning tool. This chapter is organised into three main investigation axes regarding game theory, clustering and Monte Carlo (MC) sampling. All the methodologies are presented and their application to reduce the complexity and/or the simulation time of the tool is discussed. Given that the two first approaches are not solving the computation issues, the MC methodology is retained and allows to generate typical days to be extended over the planning horizon;

- The last chapter finally presents the current version of the tool for IMG planning, which can handle more companies and more decisions. A global and thorough results analysis for an IMG with nine companies is presented in order to validate the different principles included in the updated version of the tool.

Chapter 1

Energy transition context and microgrids state of the art

With the industrial revolution and the development of electricity grids during the 19th and the begin of the 20th century, electricity needs have massively grown up. The regulated electricity grid was then composed of three components: the power plants, the transmission lines and the distribution. This vertical structure of the grid became larger and larger with the proliferation of huge power plants and the growing of the transmission grid. This evolution of the electricity grid was possible with, first, the use of coal, and then, oil to produce massively electricity.

In parallel to this evolution, physicists as E. Rutherford, A. Einstein and E. Fermi, were studying the possibility of extracting energy from an atom [1]. Around 1940, scientists started to seriously consider the possibility of creating a self-sustaining chain reaction with uranium and its nuclear fission. The first nuclear reactor was then developed in 1942 in Chicago, US. During the 1950's, nuclear energy started to be used for commercial purposes and during the next twenty years, nuclear reactors spread out massively in other countries, becoming an important part of the electricity generation in the existing grid, particularly in Europe.

At this time, the structure of the grid was still vertical with huge power plants for the electricity generation. Electricity was transported at a high voltage level in the transmission grid, then in the distribution network at a medium voltage level for industrial areas and a low voltage level for the residential areas, as illustrated in Fig. 1.1.

1.1 Energy transition in Europe and Belgium

In 1986, with the Chernobyl nuclear incident, the security of the nuclear energy was called into question and its development was massively slowed. However, the advantage of such a way of electricity generation is that it is perfectly clean regarding the carbon emissions. At the opposite, the carbon emissions linked to the use of coal and oil are huge and, moreover, the raw materials are limited on hearth. From that moment, scientists started to pay more interest to methods of generation using renewable sources of energy.

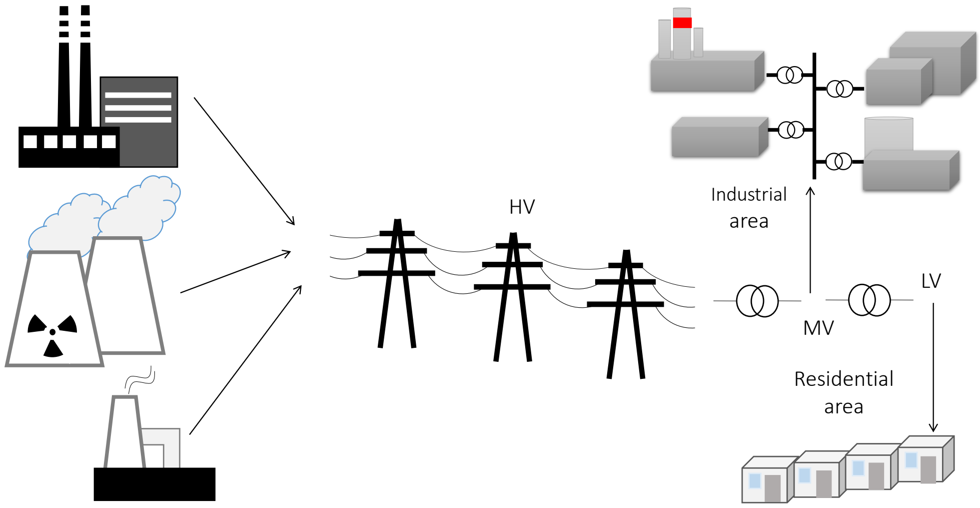


Figure 1.1 – Old grid.

At the beginning of the 2000's, given the increase of the electricity demand and the old age of the existing nuclear power plants in Europe, a real environmental and societal awareness has begun to grow. On the one side, people do not want the nuclear energy for security reasons and the lack of reliable nuclear waste treatment. On the other side, people want to decrease the carbon emission for the good of the planet. The coal power plants were progressively stopped but the electricity produced by the nuclear plants is so cheap that it has been maintained. To counter those problems and to still respond to the electricity demand, the solution of the Renewable Energy Systems (RESs) has been spotlighted. Their advantages are to use unlimited resources on earth and to have a low carbon emission, the latter being only linked to their fabrication. However, at that moment, their cost was still really expensive. Therefore, the energy problem became an environmental, societal and economical one.

In 2007, two major elements changed the European energy system: the liberalisation of the electricity market and the establishment of the 2020 European package (enacted in the legislation in 2009). From that moment, a massive energy transition has started including a change of paradigm in the electricity field, leading to a much more complex organisation of the electricity grid.

1.1.1 Liberalisation of the electricity market

Before the liberalisation of the electricity market, generation, transmission and distribution, organised as a vertical structure, were gathered within a monopolistic organisation. With the liberalisation, electricity market became a competitive market where sellers and buyers exchange amounts of electricity through a trading platform. Henceforth, only the Transmission System Operator (TSO) still has a monopole while the generation and the supply of electricity are separated and opened to competition. That means that each consumer can chose its supplier that itself can collaborate with different electricity producers. Moreover, according to the geographical area considered, different Distribution System Operators (DSOs) are active in the low voltage grid. Fig. 1.2 shows the operation of the current regulatory framework with all its actors. The part with blue arrows represents the physical part and the part with orange arrows represents the economic part.

Electricity producers are responsible for the electricity generation from traditional power plants, such as the nuclear, the gas turbine and the combined heat and power ones. Electricity generated is then physically injected in the high voltage transmission network, managed by the TSO (who has the monopole). The TSO is also the one who manages the interconnection between European transmission networks. Electricity flows then through the MV and LV distribution networks, managed by a DSO in order to be carried to the consumers. From the financial point of view, electricity amounts are purchased and sold on platforms in which the producers and the suppliers can anonymously (or not) negotiate electricity prices. Those negotiations can be realised at different time horizons according to the considered market (forward, day-ahead, intra-day or real-time markets).

The consumers are then connected physically to the DN and economically to their chosen electricity supplier. The price practised by the supplier is the commodity price from the market added to some transmission and distribution costs and to some taxes. Note that if the consumer is a producer, electricity is physically injected into the DN. For the residential prosumers ($<$ 10kW), only one meter is installed and, during those injections, the meter spins backwards. For the industrial ones, two meters are used (one for the purchasing and one for the selling of electricity) and the excess of production is purchased by their supplier at a fixed price decreased by some distribution costs.

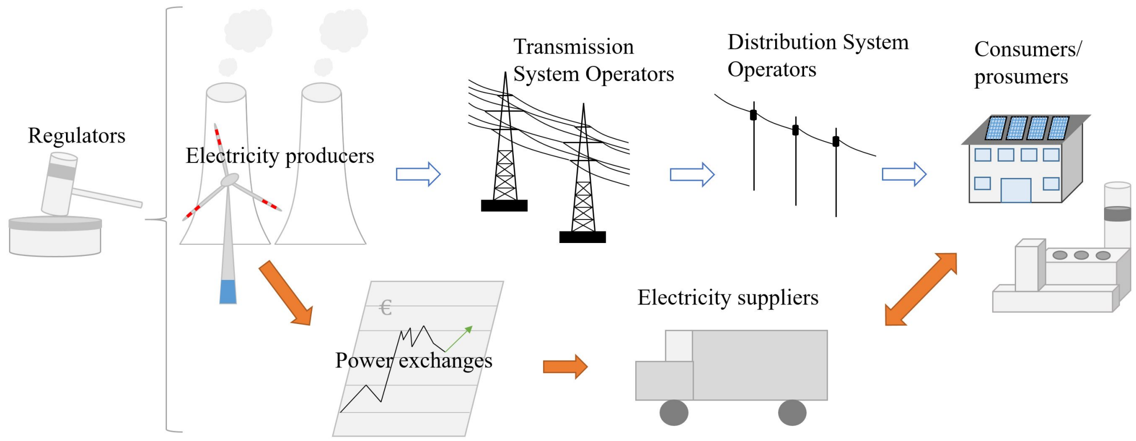


Figure 1.2 – Current regulation.

1.1.2 European energy packages

Regarding the proliferation of RESs, a significant step forward was given in 2007 with the establishment of the 2020 European package (enacted in the legislation in 2009). This package ensures that, in 2020, Europe will meet a 20% cut in greenhouse gas emissions (in comparison with 1990), 20% of Europe energy will come from RESs and the energy efficiency will be improved of 20%.

In pratice, in order to fulfil those objectives, the RESs are proliferating in two ways: the electricity producers are investing in important Wind Turbine (WT) farms (onshore or offshore), PhotoVoltaic (PV) panels installations and/or other kind of RESs (*e.g.* biomass, pumped-storage hydroelectricity, geothermal energy). On the other side, the residential, commercial and industrial areas invest in small WT and PV installations and start to be prosumers. Therefore, the electricity grid has become more and more complex as illustrated in Fig. 1.3.

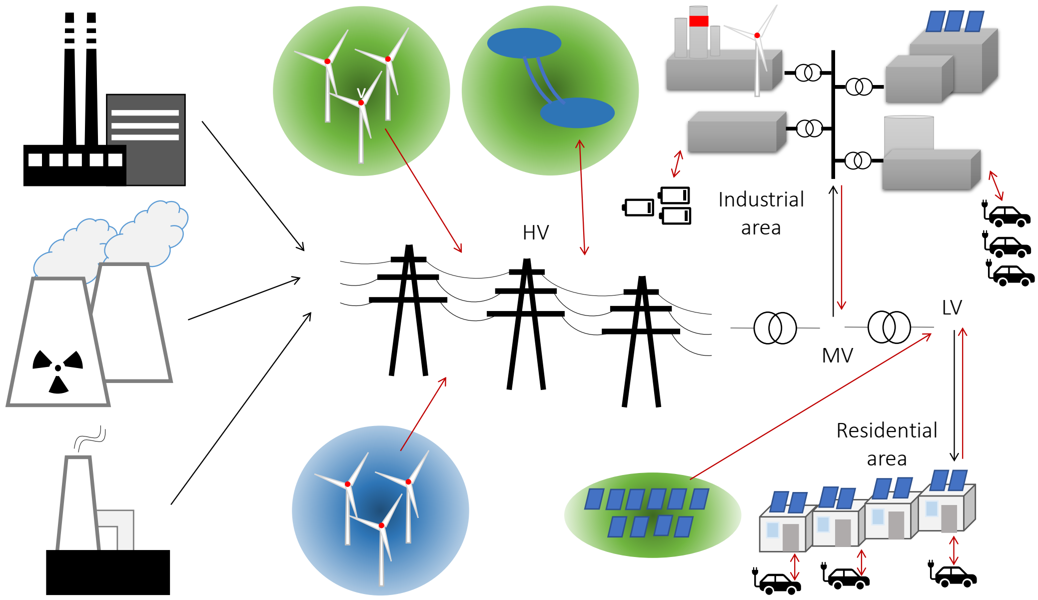


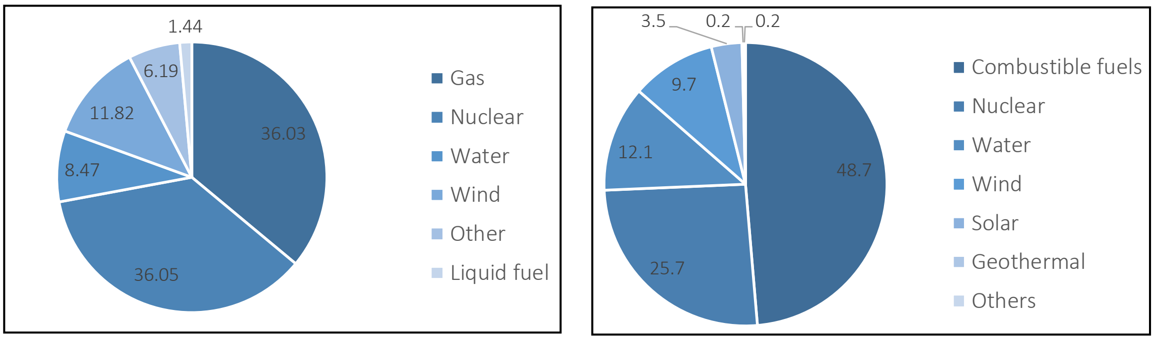
Figure 1.3 – New grid.

In Belgium, all those investments are profitable thanks to the creation of the Green Certificates (GCs). Their principle is to pay each producer for each MWh of electricity produced by a RES. In a first time, each prosumer profited of these certificates, whatever the size of its installation. Recently, the mechanism of green certificates has been contested and led to budget problems in Belgium, so that they have been removed for the small producers (PV installation under $10kW$). For industrial companies, those GCs still exist, at the current price of 65€ per GC. All the detailed mechanism of the GCs and the computation of the amount of GCs paid to a producer is detailed on the website of the CWAPE, the Walloon regulatory commission for energy [5].

From that moment, a part of the electricity generation has been said *decentralised* because WTs and PV panels are installed throughout the MV and the LV distribution networks, respectively. It means that the energy flow is no longer unidirectional in the electricity network but is now *bidirectional*. As the existing network has been built and sized for unidirectional flows (from the big power plants to the consumers), this change leads to some challenges and adaptations of the network but also of the way of consuming electricity. Indeed, in addition to their location in the grid, such RESs naturally depend on the wind and the sunshine, which are intermittent and hardly predictable. That means that the electricity produced is variable and spread over the network.

According to the European Commission report published in April 2019 [2], in 2017, around 17.5% of the Europe consumption was covered by renewable energy. Still according to this report, hydroelectric and WT generation are the most important RESs used in the electricity sector, while both PV and WT costs have drastically decreased since 2009, leading to an increased penetration of those installations.

In 2018, new European objectives have been set, aiming at a RES penetration of 32% for 2030. In 2019, European Union and Belgium are still far from these objectives. For Belgium, the electricity generation mix is available online on Elia (the Belgian TSO) website and is presented in Fig. 1.4a for 2019. For the European Union, data found in [3] show the energy mix presented in Fig. 1.4b for the year 2016.



(a) Belgian electricity generation in 2019 [4]

(b) EU electricity generation [3])

Figure 1.4 – Electricity generation in Belgium (in 2019) and Europe (in 2016).

1.2 Towards smart grids and microgrids concepts

In order to enhance the development of the RESs and ESSs while ensuring the security and the reliability of supply as well as an affordable electricity price, some technical, economic and societal challenges must be solved. Among the electricity field actors, different visions of the future electricity grid emerge.

For the belgian TSO, the future European grid must be integrated, including decentralised RESs, with huge interconnection to allow the exploitation of the local resources. Indeed, for example, the south part of Europe could be a solar hub, while the part near the North Sea could be a wind hub and the mountain regions could be water hubs. Their vision include a unique European market with active consumers. Their approach includes three main axes: the reliability, the durability and the financial accessibility [6]. Regarding Belgium, given its central position in Europe, it could become an energy junction and take advantage of this place. The RESs are still going to be developed (mainly onshore and offshore WTs and PVs) and completed by gas power plants to ensure the reliability of the system without nuclear power (that is planned to be completely stopped in 2025).

In [7], the vision of the authors for the European grid is quite close to the previous one. Indeed, it goes towards a full smart integrated and digitalised energy system including an integrated network with storage (including gas, thermal, liquid fuel and electricity networks) connected to low carbon emission electricity generation system using renewable sources (including water, solar, wind, geothermal, biomass, biogas, biofuels) and nuclear. All the system is circular by the recycling of the used materials and the carbon capture. This integrated energy system is surrounded by three other structures: a unique market platform for the European electricity and gas including dynamic pricing, a communication infrastructure allowing the exchanges of the data and a protected digital infrastructure ensuring the services and the involvement of the local systems (including industries and citizens).

In [7], the authors specify that local structures must be developed in order to ensure energy services and to develop the new roles for the prosumers (such as predicting and adjusting their load and realise peer-to-peer trades). For that purpose, **smart-microgrids** can be seen as **local structures facilitating the integration of RESs and ESSs while developing new roles of prosumers to actively participate to the new grid and market structures**.

In such smart grid and microgrid structures and with the new organisation of the electricity system, an important change occurs for the consumers. In the old system, consumers were passive and the production was adapted to the consumption in order to ensure the balance of the grid. In a smart grid, consumers become active which means that the balance of the grid is reached by the adaptation of their consumption to the generation (local or global), according to the variability of the latter. The consumers have to become familiar with notions such as load shifting and demand side management. Moreover, for some years, some new loads such as Electric Vehicles (EVs) have appeared and also have to be intelligently managed in such smart grids and microgrids.

In the literature, many surveys and reviews are gathering the research realised in the past few years in the field of smart grids, regarding the RES integration [8] [9], the ESS integration [11] but also the smart operations [10], the consumer roles and the communication technologies [8]. This work focuses more particularly on the concept of **connected microgrid**, $i.e$ a **geographically defined area of the grid, always connected to it by only one point of connection**. The impact of microgrids on the future smart grid architectures has been discussed in [12]. Inside the microgrid, the management of the RESs, ESSs, consumers and prosumers has to be properly handled while taking into account the connection to the grid. The microgrid can therefore be seen as a single entity from the point of view of the main grid. The development of microgrids allows to integrate massively new RESs and ESSs while optimising their use and therefore limiting the investments in the main network.

From the main network point of view, the microgrid can be seen either as a load node (if generation inside the microgrid is lower than its global consumption), as a generation node (if generation inside the microgrid is higher than its global consumption) or as a neutral node (if the generation is equal to the consumption in the microgrid). The exchanges inside the microgrid and between the microgrid and the DN have to be ruled by a specific pricing, which is quite difficult to define. Indeed, the electricity prices for the stakeholders of the microgrids must be attractive ($e.g$ by decreasing transmission and distribution costs) to encourage RESs installations but the other stakeholders connected to the DN, and who do not take part of the microgrid concept, do not have to be penalised ($e.g.$ by paying more grid fees).

Therefore, if a microgrid is established, direct exchanges would occur between consumers and prosumers inside of it. Those exchanges should be realised at attractive prices in order to make the microgrid profitable and then "by-pass" some steps of the current pricing, while not penalising the non-participating companies. Such an operation is obviously not allowed by the current regulatory framework.

In the literature, some research are realised about the impact of microgrids on the medium voltage network [13]. The authors show that the massive integration of microgrids in the medium voltage network has a positive impact for the transmission network by decreasing the energy losses and the operation costs but could have a negative impact on the distribution grid regarding the investment costs. However, these losses could probably be compensated by some services provided by the microgrids. In [14], the operation of the distribution network is studied through a bi-level optimisation problem taking into account the DSO and several microgrids. The conclusions indicate that the electricity prices applied influence the profit of the grid and the cost of the microgrids.

There exists some residential microgrids connected to the low voltage distribution network and including only residential load profiles. Such load profiles are defined by peak values of consumption occurring during mornings and evenings. In such residential microgrids, the main installed RESs are PV panels. However, the generation profile of such RESs occurs during the day, around midday. That means that the load and the generation profiles are not in phase leading to, on the one hand, periods of lack of generation (and then lots of electricity purchase to the main grid) and, on the other hand, periods of surplus of generation (and then lots of electricity sent back to the grid). As mentioned in the previous section, current residential systems in Belgium are connected by one meter to the grid, spinning backwards during injection.

Microgrids also concern the industrial sphere, connected in the medium voltage distribution or transmission grid. Indeed, a particular attention is devoted to the industrial sphere, given that they are responsible of an important part of the greenhouse emissions in the world (about 40% according to [15]). Therefore, improving the profitability of such installations for industrial companies, developing flexibility and services, as well as maintaining the proper operation of the grid with those powerful installations have become some active fields of research. In **Industrial MicroGrids** (IMGs), the daily industrial load profile of some companies may be more in line with the PV generation. Moreover, according to their industrial activities, some companies are in operation during nights and days, and their consumption profiles can be complementary with each other. That overlapping allows to take more advantage of the local generation. Moreover, as IMGs are connected to the MV network, the installation of WTs can also be considered, which multiplies the number of sources and generation profiles. The approach to develop, manage and operate an IMG is therefore very different from the one applied to a residential microgrid.

By way of indication, Fig. 1.5 shows the typical shapes of two (a residential and industrial) normalised load profiles along with a normalised PV generation profile.

1.2.1 Microgrids technical challenges: state of the art

In [16], a microgrid is defined by the US Department of Energy, as *"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"*.

This definition refers to the notion of grid-connected or islanded modes. In the literature, the second situation mainly concerns the developing countries (*e.g.* in Africa) where the rural

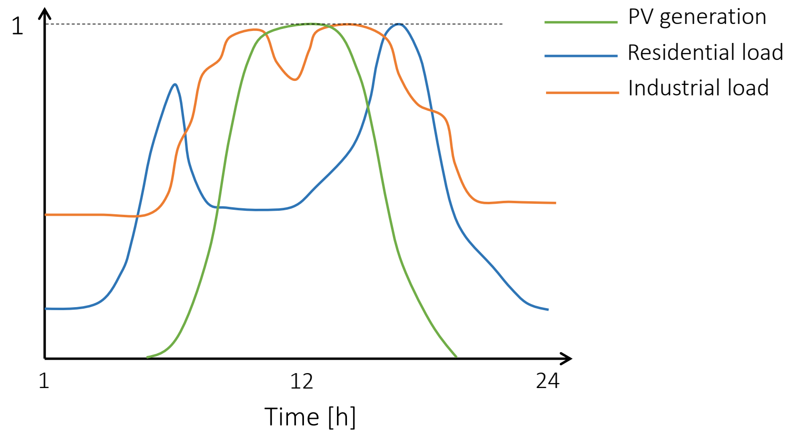


Figure 1.5 – Typical daily residential and industrial load profiles.

electrification does not exist and the development of microgrids is the only way to provide electricity [19]. This kind of microgrid may also concern some islands, disconnected from the main network. In [20], a review of the planning, the operation and the protection of such islanded microgrids is presented.

Moreover, a microgrid can be a delimited part of the main grid or a new structure. For this last case, we can find in the literature some papers relative to the topology design of such new microgrids. For example, in [21], the authors study the different topologies of connections inside the microgrid in order to provide the highest reliability in islanded mode. [22] shows that a DC structure could also be interesting, even for connected microgrids, given that PV installations and storage systems are also DC systems. The investment costs of inverters, rectifiers and transformers are therefore different and this kind of microgrid can be interesting if there is also a lot of DC loads connected to it. In [23], the design of a microgrid generation is studied in order to ensure the power quality and the energy security in every points of the microgrid, while operating in islanded mode. [24] also proposes ameliorations of microgrid architectures in order to solve certain limitations of traditional microgrids.

As previously said, this work focuses on connected microgrids. The setting up of microgrids requires investments related to the operation (including control, metering, protection and communication facilities as well as the maintenance and operation costs of the different components) [16] and the management of the microgrid. All those elements have to be economically considered in the investment planning of the microgrid. In [17], all kinds of microgrid generation and storage options are presented as well as the drivers of microgrid deployment regarding energy security, economic benefits and RESs integration. The authors in [17] also show that many of the remaining challenges rest with the regulatory framework and the market linked to these microgrids. An example of regulatory framework is also shown for a specific case in Singapore in [18]. Moreover, **the management and the ownership of microgrids is not always well defined in the literature. Their management is often reduced to a microgrid planner, operator or controller but not to a physical entity**.

The remaining of this chapter presents a technical state of the art in the four fields that concern the tool developed in this thesis: the operation of microgrids (including the energy management), the microgrids planning, the application of game theory in microgrids planning and the storage components in microgrids (*i.e.* the ESSs and the EVs). Finally, a conclusion summarises the originalities of the developed tool in light of the existing literature.

Microgrids operation and energy management

Microgrids operation performance have already been demonstrated in the literature and energy management systems have also been proposed, mainly for isolated microgrids [25], [26] in order to maximise the use of RESs and the lifetime of ESSs. In [27], an online energy management system for connected microgrids is developed, taking into account the power flow and the constraints of the distribution network. The problem is formulated as a stochastic optimal power flow and is almost as efficient as an offline algorithm.

Regarding the microgrid operation, some energy exchanges have to be managed between the stakeholders (peer-to-peer exchanges) [28] or between different microgrids. Regarding this last concept, for example in [29], a real-time interactive energy management system is developed in order to manage several microgrids connected to the DN. After the management of the generation and the 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 fulfil their needs. For the internal operation, the microgrid operational management is performed using a dedicated control scheme. In [30], a comparison between centralised (microgrid central controller) and decentralised (local controllers) control architectures is presented, considering the power dispatch according to both economic and environmental objectives. In the developed tool, the microgrid operation is centralised by a MicroGrid Energy Manager (MGEM) while also taking into account the individual freedom of each stakeholder regarding their energy management.

Grid-connected operation can also be realised in order to provide some services to the main grid. At the transmission grid level, in [31], microgrids are participating to the frequency regulation through the provision of ancillary services and therefore to the regulation market. Regarding the DSO, given the development of the RESs, the deployement of smart grids and the operation of the microgrids, it must face new challenges. In [32], the role of the DSO in smart grids is considered through an improvement of the network operation by decreasing network losses, considering uncertainties on electricity markets and managing demand response.

Regarding microgrids, different control structures that include the DSOs potential actions have already been proposed in the literature but it often is a bi-level structure, considering the DSO on the one hand and the microgrid on the other hand. For example, in [33], the interaction between the DSO and the microgrids in modelled and used to engage the microgrids in the peak ramp minimisation of the grid. For that purpose DSO and microgrids both solve local problems to ensure a global welfare for the first and to optimise the generation and the ESS for the second, respectively. A principle of incentives given by the DSO to motivate the microgrid to reduce the peak ramp is also considered. In [34], the authors show the benefits for a microgrid (seen as a whole) in a new tariff structure established in the distribution grid.

In the work presented in this thesis, the DSO will be considered for both its role outside the IMG but also inside the IMG. By this, we mean that it can take the role of MGEM. And,

even if it is not the MGEM, it is considered in the planning problem through the exchanges between the IMG and the main grid, as well as through a new established pricing scheme.

The operation of the microgrid also rests with the adaptation of the consumers loads to the new generation systems. Indeed, from now on, the consumers are not passive anymore in the grid but are active stakeholders. For that purpose, in both residential and industrial spheres, some Load Management (LM) can be performed by the microgrid stakeholders.

Regarding residential LM, in [35], the authors present the principle of a collaborative consumption inside a residential microgrid. They show that, given some prioritisation of the loads, the participation to this mechanism of energy management can provide benefits for the residents. This principle could also be applied in the industrial sphere, even though the constraints and the goals are differents which lead to other considerations. Indeed, in [36] focusing on the industrial LM, the accent is set on the peak of consumption. The authors try to minimise the peak to average ratio in order to maximise the profit.

The industrial LM rests on the shifting of different industrial processes according to their priority and constrains. LM methods presented in [36], [37] also include other parameters such as raw materials, final products and wastes. Reference [38] shows that, practically, industrial LM methods can be different according to the industrial process considered and the resources of the industries. Therefore, smart load management can be used to adapt the load to the generation, to minimise exchanges with the main grid or even to perform peak shaving [30]. The LM principle set in the tool developed in this thesis is a general one but conceived as flexible as possible in order to consider in a realistic way the constraints linked to process. It will allow to fit the load to the generation and to decrease the load peak (which is an important part of the electricity bill in Belgium).

Microgrids planning

Whatever the kind of microgrid, its planning operation is important in order to observe the impacts of such a microgrid for the participating consumer(s)/prosumer(s) and to convince all of them to be part of it. Indeed, in [39], the authors study the installation of PV in industries and compare the costs of traditional generators (investment, operation and maintenance costs) with the PV solution, which is globally more interesting. In that work, it is also shown that a storage system becomes financially attractive only after many years.

The planning of different kind of microgrids is also studied in the literature in order to see their benefits on the development of the RESs. For example, in [40], the notion of provisional microgrids is defined as a complement of classical microgrids, always connected to them, and to allow the islanded mode of them. The authors show that such provisional microgrids are beneficial to the deployment of RESs in the distribution network including microgrids. In the same idea, the planning of microgrids is also used to envisage the possible cooperative investments [41] and the interconnection possibilities [42] inside and between small microgrids.

Various optimisation methods for the planning of microgrids have already been presented in the literature. Some of them only take into account the short-term planning (typically hourly)

[43] and other ones decompose the optimisation problem according to two time scales [44], [45]. Indeed, in [43], the authors perform hourly optimisations and use a Genetic Particle Swarm Optmisation method to compute the Expected Energy Not Served of its microgrid and then to define the number of units of PV, wind and diesel generator(s) to install in order to meet a targeted reliability level for an islanded microgrid. The other methods decompose the problem in a main one for investments and a sub-one for operation. Optimisation is performed based on an objective function written for the microgrid as whole. In the eco-industrial park studied in [30], at the opposite of the conventional planning problems, the objective function is not an economic one but is formulated in order to decrease CO_2 emissions and, consequently, the use of fuel.

The proper planning of a microgrid also includes a proper forecast operation of the latter. This is why the planning problem, which is a long-term time horizon problem, often includes a looped shorter-term time horizon energy management problem. In that way, among the previous cited works of the literature, in [44] and [45], the authors combine a long-term investment problem with a short-term operation management through an optimisation formulation. However, all of them consider the benefits of the microgrid composed of several stakeholders as a whole. In the same idea, [46] presents a bi-level multi-objective optimisation problem in which the upper problem deals with the dispatch of the RESs by the distribution network to reduce power losses and to improve the voltage profile and the lower problem is related to the microgrid generators operation. In [46], both problems concern the microgrid: the goal of the upper one deals with the microgrid design while the lower one with its operation, with the carbon emissions and peak of power as criteria. Again, the microgrid is seen as a whole.

Moreover, the planning of microgrids is also important for the sizing of the microgrid components. The objective function must be defined according to the first goal of the microgrid development. For example, in [48], the authors focus on the self-consumption of the microgrid while in [49], the authors want to evaluate the benefits of the microgrid in the context of ancillary services provision by a supplier. In the developed tool, different sizes of investments could be considered in order to evaluate their impacts on the IMG behaviour and for the DSO.

In the literature, some papers also take into account the DSO in the planning of microgrids. In [50], a bi-level optimisation is established in order to, on the one side, ensure the minimisation of the costs inside the microgrid by the microgrid planner and, on the other side, to ensure the reliability of supply for the DSO. In this problem, the microgrid can be a reserve capacity for the DSO. In this paper, the authors also define the new role of the DSO (*e.g.* regarding balancing). In [51], the authors present a methodology in which the microgrid owner plans its investments and then, the DSO checks if the predicted profile at the point of connection can be handled by the distribution grid. If it is not the case, new limits are set up for the optimisation problem of the microgrid planner.

In the planning tool developed in this thesis, the goal is to consider individually each stakeholder of the microgrid and the DSO, and not only the microgrid as whole on one side and, potentially, the DSO on another side. The ultimate objective is to develop greener areas while decreasing the electricity bills of the participating companies as well as to observe and limit the impact for the DSO.

A major difficulty of the planning issue comes from the uncertainties of different parameters such as weather conditions, RES generation, market pricing and the use of flexible loads [44]. In [52], the planning of microgrids is considered with different generation scenarios and microgrid costs. In some of the previously cited works, probabilistic optimisation methods are also used (as $e.g.$ in [19], [42]).

Microgrids and game theory

Another difficulty comes from the fact that many stakeholders (as the DSO, the microgrid members and sometimes even other entities) must be taken into account in the planning and/or operation problem(s). Those actors may also have different or even conflicting objectives as previously presented regarding the DSO and the microgrid planner. Therefore, the problems become multi-agent and multi-objective. To solve such problems in a way as fair as possible, game theory can be used. Indeed, game theory allows to solve problem by the consideration of all actors in a game in order to find a solution ensuring a global welfare. This solution may be or not the optimal one but is however such that no one would like to deviate from it.

Appeared at the beginnning of the 20^{th} century in its simplest form, the concept of game theory has been widely studied and developed in the mathematical and economical fields since the middle of the same century [53]. Today, the field of game theory is wide and includes lots of different games as well as ways to solve them. It is applied in lots of fields, such as economics, sociology or politics. In the electricity field, it has already been exploited to manage some electricity markets, the customer reliability provision [54], signal processing [55] and load control decisions [56] among the concerned agents.

The game theory and its particular application in this work will be further developed in the next chapter. However, in the literature, game theory has already been used for different purposes in smart grids ($i.e.$ regading the maximisation of RESs benefits [57] and energy managament [57], [58]) and microgrids. In microgrids, two main applications can be distinguished.

The first one is to use game theory to manage the relation between microgrid(s) and the main grid as well as the interaction between microgrids and electricity markets. In [59], game theory is used to deal with the competition between the manager of microgrids and the DSO and to maximise their benefits taking into account the retail market. In [60], the authors propose a cooperative game (between the DSO, a microgrid investor and the consumers of the microgrid) in order to see how the microgrid development could have an impact on the market efficiency and how to divide the benefits among the different stakeholders. Game theory can also be used for energy trading among microgrids to try maximising their respective profits [61]. In [62], the game is set up as a leader-follower game allowing the adjustment of the electricity price from RESs generation by the microgrid operator.

The second application field of game theory is relative to the internal management of the microgrid. In [63], game theory is used inside a microgrid and the different players are the components of the microgrid (such as the power, the battery and so on). The goal of game theory is to reach an equilibrium that ensures the proper operation the microgrid and the proper use of its resources. In [64], the game used respects the principle of leader-follower (it is called a

Stackelberg game). Therefore, the leaders are the generation units inside the microgrids regarding the amount of electricity generated and the followers are the consumers regarding their needs (including an ESS). A similar principle is presented in [65], in which the microgrid operator is the leader that needs to manage the PV generation while the prosumers maximise their profits (including demand-response). [66] also presents game theory to manage the generation inside the microgrid, while taking into account some technical constraints regarding power flows and voltage angles.

In [67], game theory has also been used to model the peer-to-peer exchanges inside a microgrid. Game theory is therefore used at two levels: on the one side, to define the electricity price among the producers (non-cooperative game) and, on the other side, to allow the consumer to select their producer (dynamic evolutionary game). Regarding the management of the loads, in [68], a game theoretical framework is established to schedule LM inside residential communities for minimising the energy costs.

The application of game theory in the tool elaborated in this thesis is quite different given that it is used at two levels: firstly, to plan the Long-Term (LT) investments but also to manage, at a Short-Term (ST) time horizon, the peer-to-IMG and the grid-to-IMG exchanges, including pricing and LM.

Microgrids components: EVs and ESSs

The development of microgrids is also strongly linked to the deployment of some new grid components such as the Electric Vehicles (EVs) and the Energy Storage Systems (ESSs). Their integration in smart grids and microgrids is largely presented in the recent literature, including, notably, the sizing, the control and the economic aspects. In [69], a general review of the current battery technologies, costs and application in the grid is presented. In [70], the authors gather all kinds of ESSs technologies that have already been used or that are future challenges in the specific context of microgrids.

The planning and the sizing of ESSs is developed in a general way in distribution networks [71] as well as for more specific application and use inside microgrids, *e.g.* to better fit the intermittent generation with the loads and to allow an increase of the benefits for the microgrid participants. In [72], the capacity of the installation is defined through an iterative algorithm based on the time of return on investment and the annual benefit of the microgrid, taking into account the PV and WT generation as well as the microgrid load.

Regarding the control and the optimal use of ESSs in microgrids, in [73], the authors propose an optimisation algorithm of several ESSs inside a microgrid taking into account both the constraints of the batteries (regarding charge and discharge and its efficiency) and the grid constraints inside the microgrid. They show that their algorithm allows the minimisation of the costs and therefore proves the benefits of ESSs. In the same idea, a control strategy of an ESS is proposed in [74] to reduce both the operating cost of the consumers and the amount of energy exchanges with the main grid.

The integration of the EVs in smart grids has been widely studied in the literature. Their role in the new energy system is important and multiple, given that EVs are new types of load but can also be seen as a storage system that can provide services to the grid. The EVs charge and discharge scheduling leads to an additional uncertainty in the grid and, therefore, needs to be smartly managed. In [75], different management strategies (centralised or decentralised) as well as different modelling methodologies (such as linear, quadratic or dynamic programming) are presented.

The daily planning of an EVs fleet charge has also been studied in [76]. The authors present two optimisation methodologies (a linear and a quadratic) to minimise the costs charge of the EVs fleet while taking into account the constraints linked to the needs of the vehicle users regarding the state-of-charge of the battery and the charging time. A similar idea is developed in [77], in which the charge of the EVs fleet is optimised through a grid agent that coordinates the energy utilisation according to the renewable generation and prices. EVs can also be seen as a storage system or used in combination with other ESSs. In [78], an optimisation of the EVs charge scheduling is presented and the ESSs are used to deal with the uncertainty of the scheduling prediction. The interactions with the day-ahead and real-time market are also taken into account.

Inside microgrids, the EVs are used to take advantage at best of the renewable generation in [79]. Some additional services can also be considered, as $e.g.$ in [80]. In that work, the EVs trips are managed to minimise the costs of the microgrid by balancing at best the renewable generation (decrease the uncertainty of the microgrid load and generation profiles) and by smoothing the load profile ($i.e.$ decrease the microgrid power seen from the main grid).

In the tool developed in this thesis, the ESSs and EVs can also be taken into account, but in a quite simple way given that the first goal of the tool is to plan the IMG development on a LT basis. Indeed, more complex considerations of the ESSs and EVs operation could lead to a huge simulation time given that this kind of elements needs to be managed daily in a planning tool which will typically consider a 20 years time horizon.

1.3 Conclusion

This work focuses on the investments planning inside connected IMGs, while considering a proper internal and external (with the main grid) energy management. Inside the tool developed in this thesis, each company is considered individually as a stakeholder, as well as the DSO and the Industrial Estate Operator (IEO).

For that purpose, the tool developed in this thesis differs from the existing literature in different points:

- The role(s) and the objective(s) of the DSO, the IEO and the companies are properly defined. Moreover, the ownership of the IMG and the MicroGrid Energy Manager role are also formalised, which are often confusing in the literature;
- The investments are realised by the companies and each company is a full-fledge stakeholder. The planning decisions are therefore considered and analysed for each stakeholder

individually and not for the microgrid as a whole. Moreover, all the stakeholders are considered at the same level (not with leaders and followers as in some of the previous references);

- As some of the previous references, the tool is implemented as a two time horizons decision making process: a first time horizon for the Long-Term (LT) investments decisions and a second one regarding the daily energy management and pricing. However, both time horizons are using Game Theory (with a non-cooperative game to be realistic and respect the confidentiality issues between the companies);

- Regarding the Short-Term (ST) energy management, a peer-to-IMG energy exchanges mechanism is defined making the assumption that, inside the IMG, the current regulatory framework is not applied. The possibility of defining a new framework, including a pricing scheme that is favourable for the participating companies (*i.e.* with the goal to promote investments and to decrease the electricity bills) is therefore allowed;

- The tool allows the adaptation of the parameters for different LT and ST pricing policies as well as different levels of investment quantities;

- The consideration of additional mentioned elements of smart and micro grids such as LM and ESSs, as well as the shared investments is also achievable through the proposed planning tool.

Chapter 2

Long-term planning of industrial microgrids: concepts, challenges and methodologies

This chapter is, first of all, dedicated to the proper description of the Industrial MicroGrid (IMG) concept. For that purpose, the notion of industrial estate and IMG are defined and compared. Inside such IMGs, the participating stakeholders are the first key element to consider. Their profiles as well as their goals and resources are different and should all be considered in the planning tool. The second key element of the planning tool is the internal regulatory framework that will be considered. The current one has some restrictions that will be neglected in order to develop an IMG environment, allowing some new features. Of course, a planning tool rests on some decisions leading to decision-making process challenges, for which the main executed methodologies are described and generalised in this chapter.

2.1 From industrial estate to industrial microgrid

The current distribution network is composed of geographically defined industrial estates, gathering together different kinds of companies as offices, workshops or industries. The land on which an industrial estate is developed belongs to an Industrial Estate Operator (IEO). Inside an industrial estate, each company is independent and manages its activities, its electricity bill and its electricity supplier freely. Each company is a consumer seen from the distribution grid point of view. Moreover, each company is free to invest in RESs and/or ESSs in order to manage its own consumption and therefore to become a prosumer seen from the Distribution Network (DN) point of view.

In the current belgian regulatory framework, it is completely forbidden to directly share electricity between companies inside an industrial estate. Each company is connected to the medium voltage DN by its own transformer, as illustrated in Fig. 2.1, and all the electricity consumed or produced is directly exchanged with the DN, via an electricity supplier chosen by the company.

An IMG is an industrial estate in which a MicroGrid Energy Manager (MGEM) entity is managing the electricity exchanges with the distribution network as well as between

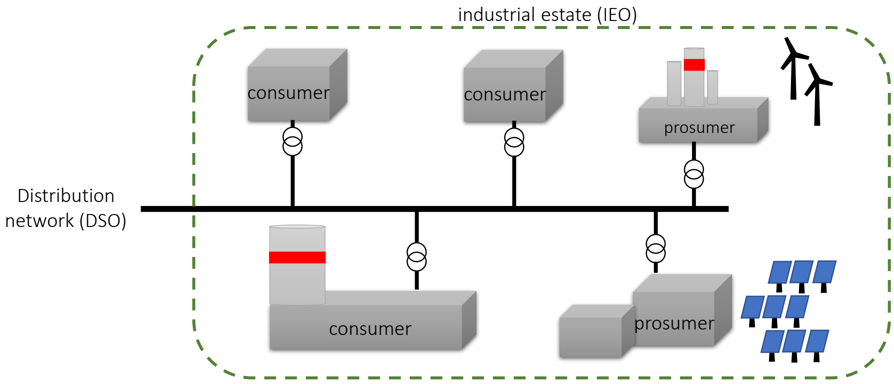


Figure 2.1 – Industrial estate.

companies. The major hypothesis is that, inside the IMG, the current regulatory framework is by-passed. A new one, called IMG regulatory framework, is defined gathering new electricity prices, new fees and new rules for the energy exchanges.

The goal of such an IMG, and of such a new regulatory framework, is to promote the development of RESs and ESSs, increase the self-consumption of all companies as well as better manage exchanges with the DN. If the industrial estate already exists, the electrical topology of the industrial estate must be conserved and a minimal amount of replacing and reinforcing investments should be realised. Therefore, all consumers and prosumers are still physically connected to a main radial line and not directly connected between each other (no direct line from a stakeholder to another one). This allows the MGEM to regulate and control the energy exchanges inside the IMG and between the IMG and the DN. In order to communicate and to exchange the necessary details, the companies and the MGEM must rely on communication channels (blue links for the companies and red link for the DSO). The principle of the IMG is illustrated in Fig. 2.2.

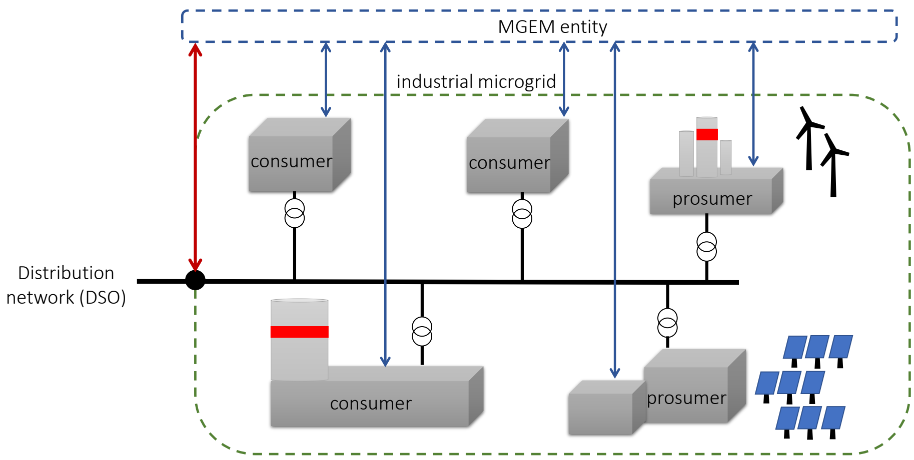


Figure 2.2 – Industrial microgrid.

Such an IMG implies, to be relevant, lots of investments in RESs and ESSs, which can be realised by the stakeholder individually or in a collaborative way. In order to avoid overloading the grid and to avoid expensive and useless investments, an investment planning must be established as well as the rights and the actions of each stakeholder. The developed tool needs therefore to consider the following elements, that are the next subjects of this chapter:

- The goals, resources, rights and duties of each stakeholder;
- The new IMG regulatory framework;
- The different time scales of the decisions that can be taken by the stakeholders to fulfil their goals.

2.2 Industrial microgrid stakeholders: goals and resources

One of the goals of the IMG concept is to allow companies to realise some savings on their electricity bills. However, all the companies are linked through the IMG regulatory framework and, therefore, their benefits are depending from each other. Inside an IMG, the stakeholders can be classified into different categories:

- The prosumers;
- The consumers;
- The DSO;
- The IEO;
- The MGEM.

The developed tool has to consider all of them, with their respective objectives that could be different, and even conflicting, leading to a multi-agent and multi-objective problem to solve. For that purpose, this section details each kind of stakeholder and summarises their goals and resources.

Prosumers

The objectives of a prosumer are multiple. The first is to self-consume a maximum of its own electricity generation. This is possible by doing, *e.g.*, some LM in order to fit at best its consumption profile to its own generation. Its second objective is to decrease the difference between the purchasing price of electricity from the DN and the selling price of its excess of generation (not directly consumed). Indeed, in the current regulatory framework, for industrial companies, the electricity selling price of electricity to the grid is much smaller than the electricity purchasing price (the current pricing will be detailed further in this chapter). By participating to the IMG and, consequently, to an internal specific pricing thanks to the IMG regulatory framework, the selling price is expected to be higher than before the IMG configuration.

The possibility of investing in an ESS can also be considered. In that case, its objective will be to reduce the time of return on investment of this expensive technology. The latter may change the policy to adopt by the prosumer and have an impact on the exchanges with the other stakeholders of the IMG and with the DN. Indeed, the prosumer will first self-consume its own generation, then store a maximum of its surplus of generation in order to self-consume it at another time and, finally, sell its remaining surplus to the IMG community.

Objectives: *reducing the electricity bill, increasing the self-consumption rate, reducing the difference between purchasing and selling prices, decreasing exchanges with the DN, reducing the time of return on investment of RES and ESS.*

Possible actions: *doing some load management to fit consumption and generation, investing in ESS or in new RES(s).*

Consumers

The main objective of a consumer is to decrease its electricity bill. This is possible thanks to attractive prices of the electricity purchased inside the IMG. However, as a consumer does not have its own generation, this electricity can not always be available. It depends on the generation and the consumption of the corresponding prosumer(s) at the same time because the prosumers self-consume a maximum of their own generation in priority, as explained above. Another way to decrease its electricity expenses is to do peak shaving. Indeed, the purchasing price of electricity includes a part linked to the peak of consumption of the industrial consumer. Reducing this peak will then lead to important savings. Globally, the goal of consumers is to limit the exchanges with the DN, given that the price of the purchased electricity will not change (as explained above). A consumer can also invest in a RES and hence become a prosumer and, therefore, fulfil new objectives linked to its own generation.

Objectives: *reducing the electricity bill, peak shaving, decreasing exchanges with the DN.*

Possible actions: *doing some load management, investing in RES (and ESS).*

Distribution System Operator

In the current regulatory framework, the DSO perceives distribution costs for each MWh of energy flowing in the DN. The DSO also perceives an amount linked to the peak of consumption of each connected company. If the companies are gathered inside an IMG connected in a single point of connection to the DN and, if the DSO is not included in the planning problem, the DSO would perceive only the costs for the energy carried and the peak of consumption of the IMG globally. However, the amount of energy transited would probably be less than the sum of the amounts of energy which would have been transited without an IMG. The peak of consumption of the IMG as a whole would similarly be also decreased. Those differences would represent a shortfall for the DSO. If the DSO is taken into account in the planning problem, the management policy would consider that its objective is to have at least the same benefit as in the situation without an IMG. Moreover, from a technical point of view, the planning process should ensure the proper operation of the IMG and the DN while meeting the power quality standards.

Objectives: *economically compensating the decrease of exchanges with the DN, ensuring the proper operation of the network.*

Possible actions: *defining new pricing.*

Industrial Estate Operator

The IEO is responsible for the current industrial estate. In Belgium, this "inter-communal" organisation is responsible for the economical development of the territory [81]. Recently, the IEO has faced new challenges linked to the RESs proliferation and has massively invested in the development of greener industrial estates. Its objective is really different from the other stakeholders because the IEO does not want to make "direct" benefits with an IMG but some "indirect" ones in order to further develop the industrial estate. This means that it could provide some aids, invest in some technologies and realise transformations to help the companies of the industrial estate. With more attractive electricity prices in such IMGs and attractive aids for installations inside of them, the socio-economical impact (new companies, expansion of the current companies, new jobs, etc.) would be seen as a benefit for the IEO.

Objectives: *making indirect benefits (socio-economic), making attractive electricity prices, developing greener industrial estates.*

Possible actions: *giving financial aids for RESs and ESSs investments to (new) prosumers, investing in RESs and ESSs, participating in the electricity pricing.*

Microgrid Energy Manager

The MGEM is a full-fledged stakeholder of the IMG. Its particularity rests in its role that can be played by one of the previously mentioned stakeholders, $i.e.$ the DSO, the IEO or some consumers/prosumers. Moreover, the possibility of an external manager could also be considered. It could be an independent entity (which wants to make direct benefits) or a public entity (without any money benefits wished).

No matter who the MGEM is, its roles are divided into two main parts:

- At the initial time of the IMG creation, run the planning tool developed in this thesis according to the historical load and generation information of each consumer/prosumer (shared under a confidentiality contract) in order to give advice to the IMG stakeholders about their long-term investments while taking into account a proper Short-Term Energy Management (STEM). For that purpose, it has to:
  - gather and classify the historical data of the participating companies according to their consumption habits;
  - gather the wishes of each company (for investments);
  - complete necessary information (inputs) to run the planning tool.
- Daily (one day for the next one), properly manage and regulate the exchanges inside the IMG (peer-to-IMG exchanges) and between the IMG and the DN (IMG-to-DN exchanges) as well as the LM possibilities

As the MGEM remains a full-fledge stakeholder of the planning problem, its objectives are therefore, besides its own ones (other role than MGEM) and the respect of the objectives of all the other stakeholders, to ensure the proper operation of the IMG. For that purpose, a fee is included in the new IMG regulatory framework as a remuneration for this management role.

2.3 New IMG regulatory framework principle: cash-flows computation

The main particularity of the IMG is that the participating companies are not anymore subject to the existing regulatory framework. The new regulatory framework includes three parts: the new system of costs allocation, the definition of the commodity trend price inside the IMG and, finally, the management of the energy exchanges. The energy exchanges are now authorised and even promoted inside the IMG (peer-to-IMG exchanges) and the same holds for the exchanges with the DN (IMG-to-DN exchanges). This last step will lead to the computation of daily cash-flows for each stakeholder.

2.3.1 Costs allocation: comparison between the current and the new regulatory framework

In order to better understand the pricing principle, let us recall the current electricity cost allocation in the Belgian framework. For a company connected to the MV DN, the purchasing electricity price is currently composed of several components:

1) **Commodity price $\Pi_{out,p}$ (€$/MWh$).** This price represents the electron price, defined by the electricity supplier. This price is the one concluded by the supplier on the electricity market, added to the supplier fee;

2) **Distribution costs.** Those costs are divided into three main parts:

   - The energy part $\Pi_{out,p}^{fee,d}$ (€$/MWh$), paid by each consumer according to its energy consumption over the considered billing period;
   - The power part $\pi_{out,p}^{peak,d}$ (€$/kW/year$), paid by each consumer according to its peak of consumption over the last 12 months;
   - The metering part π_{out}^{met} (€$/year$), which is a yearly amount, fixed for each consumer.

3) **Transmission costs.** Those costs are composed of two parts: an energy part $\Pi_{out,p}^{fee,t}$ (€$/MWh$) and a power part $\pi_{out,p}^{peak,t}$ (€$/kW/year$), which are computed in the same way as the distribution costs;

4) **Reactive energy cost (€$/MVarh$).**

5) **Taxes**, $\Pi_{out,p}^{taxes}$, including connection and overload taxes (€$/MWh$), both paid by the consumer according to its energy consumption over the considered billing period;

6) **Renewable fee**, $\Pi_{out,p}^{new}$ (€$/MWh$), depending on the energy supplier.

The selling price of electricity is composed of the commodity price, $\Pi_{out,s}$ (€$/MWh$), decreased by some distribution costs. Those distribution costs include an energy part $\Pi_{out,s}^{fee,d}$ (€$/MWh$), paid by each producer according to its energy sold over the considered billing period, and a daily fixed part, π_{out}^{met} (€$/day$), linked to the metering.

New IMG regulatory framework

For an IMG connected to the DN by a single connection node, two types of pricing are defined. The first one is for the external exchanges, $i.e.$ between the IMG and the DN. The second one deals with the internal exchanges, $i.e.$ for the peer-to-IMG exchanges inside the IMG.

For the IMG-DN exchanges, the current pricing remains unchanged in order to be fair with the non-participating companies (regarding the repartition of the network costs). However, two components are computed in a different way: the power part and the metering part. The first one is linked to a new computation way of the peak of consumption (and a new pricing of it) of each consumer inside the IMG. This last one will be developed in details further in this manuscript. The second one is linked to the fact that the IMG is connected by a single node to the DN and so, there is only one meter between the DN and the IMG. Therefore, the metering cost is only paid once by the MGEM and then, divided between all the participating companies of the IMG. Each prosumer/consumer pays π_{out}^{met} at each hour and the DSO perceives $(S-1)\times\pi_{out}^{met}$ (where S is the number of stakeholders inside the IMG, including the MGEM).

For peer-to-microgrid exchanges, the purchasing price is composed of two main components:

1) The **commodity price** $\Pi_{in,p}$ ($€/MWh$);
2) The **MGEM fee**, which is divided into two parts:
    - The energy part ($€/MWh$), linked to the MGEM role, regardless of the one who holds this role, for the management of exchanges and the maintenance/investments of the lines inside the IMG ($\Pi_{in,p}^{fee}$);
    - The power part, linked to the global peak of load of the IMG ($€/kW/day$, $\pi_{in,p}^{peak}$, computed according to a peak ratio r_P of the existing distribution peak pricing).
3) The **DSO fee**, set up to offset the losses due to the decrease of exchanges with the distribution network ($€/MWh$, $\Pi_{in,p}^{dso}$).

The selling price inside the IMG is simply composed of the commodity price $\Pi_{in,s}$ ($€/MWh$) decreased by a little energy fee amount for the MGEM $\Pi_{in,s}^{fee}$ ($€/MWh$).

The fees inside the IMG are defined according to a ratio, $i.e$ a defined percentage of the internal hourly commodity price $\pi_{in,p,h}$ for each hour $h=1,...,24$. Regarding the metering costs for companies inside the IMG, an IMG metering cost π_{in}^{met} ($€/day/prosumer$) is considered, for the consumer and the producer. Moreover, as the IMG is always connected to the IMG, the DSO metering cost is considered for each hour for each prosumer/consumer (π_{out}^{met}).

Note that, in the current regulatory framework, each produced MWh by a PV installation is remunerated by green certificates (GC). The number of GC depends on the power of the installation. Those GC are still considered in this tool, $i.e.$ each MWh produced by a prosumer allows an earning of π^{GC}. Besides, the maintenance and operation costs of the RESs are considered up to 2% of the initial investment cost per year.

Finally, the developed tool also takes into account the difference between the full prices (between 7am and 10pm) and the off-peak hours prices (from 11pm to 6am).

2.3.2 IMG commodity price daily trend

In the electricity pricing inside the IMG, the commodity prices of purchasing $\Pi_{in,p}$ and selling $\Pi_{in,s}$ as well as the amounts of the new fees have to be studied. For that purpose, the trend of the electricity pricing inside the IMG will be defined according to the trend of the electricity pricing outside the IMG according to four possible trends of the daily electricity prices:

- First case: same trend as the external prices;
- Second case: constant price;
- Third case: opposite trend compared to the external prices;
- Fourth case: inversely proportional to the generation inside the IMG.

Over one day (24 hours), the vector of the external electricity purchasing price, $\Pi_{out,p}$, is defined by $\Pi_{out,p} = [\pi_{out,p,1}, ..., \pi_{out,p,24}]$. In the **first case**, to encourage the exchanges inside the IMG, the internal electricity purchasing price, $\Pi_{in,p}$, has to be lower than $\Pi_{out,p}$. A ratio out-in prices, $r_{out/in}$, such as $0 < r_{out/in} < 1$ is defined, and $\Pi_{in,p}$ is computed by (2.1). The selling price inside the IMG, $\Pi_{in,s}$ can be equal or lower than the purchasing price. The ration purchase-sale, $r_{p/s}$, such as $0 < r_{p/s} < 1$ is defined, and $\Pi_{in,s}$ is computed by (2.2).

$$\Pi_{in,p} = r_{out/in} \times \Pi_{out,p} \tag{2.1}$$

$$\Pi_{in,s} = r_{p/s} \times \Pi_{in,p} \tag{2.2}$$

For the **second case**, all the elements of $\Pi_{in,p}$ are identical for $h = 1, ..., 24$ and defined as the mean of the daily vector $\Pi_{out,p}$ (see 2.3). $\Pi_{in,s}$ is computed by (2.2).

$$\pi_{av,day} = \frac{1}{24} \sum_{h=1}^{h=24} \pi_{out,p,h} \tag{2.3}$$

For the **third case**, the $\Pi_{in,p}$ is computed in such a way that its trend is the opposite one compared to $\Pi_{out,p}$, against $\Pi_{av,day}$ ($\Pi_{av,day} = \pi_{av,day}$ for $h = 1, ..., 24$). $\Pi_{in,p}$ is computed by (2.4) and the principle is illustrated in Fig. (2.3) with $r_{out/in} = 1$. $\Pi_{in,s}$ is computed by (2.2).

$$\Pi_{in,p} = r_{out/in} \times (\Pi_{av,day} - (\Pi_{out,p} - \Pi_{av,day})) \tag{2.4}$$

Finally, for the **fourth case**, we need to define $r_{g,h}$, the ratio between the hourly generation $[p_1, ..., p_{24}]$ and the mean generation over the day, denoted $P_{av,day}$ (see 2.5). $\Pi_{in,p}$ is then defined as the ratio between the average external price $\pi_{av,day}$ and $r_{g,h}$ (see 2.6).

$$r_{g,h} = \frac{p_h}{P_{av,day}} \tag{2.5}$$

$$\pi_{in,p,h} = \frac{\pi_{av,day}}{r_{g,h}} \tag{2.6}$$

This formula is subject to two constrains: if generation is equal to zero at hour h, $\pi_{in,p,h} = \pi_{av,day}$ and $\pi_{in,p,h}$ cannot be higher than $\pi_{out,p,h}$. An example of such a price computation is presented in Fig. 2.4. $\Pi_{in,s}$ is computed by (2.2).

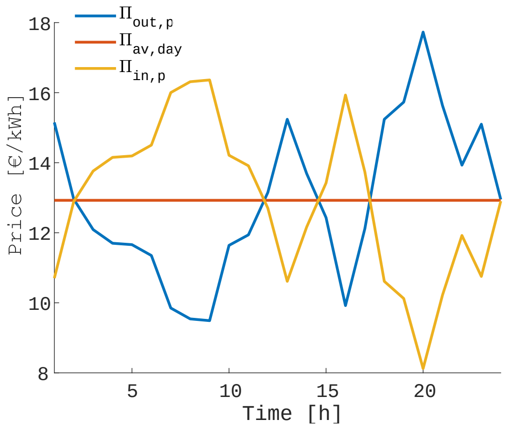
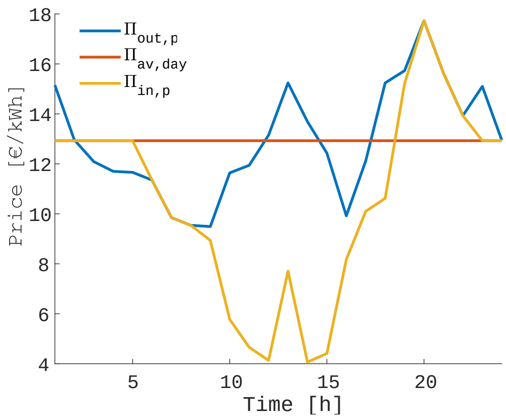
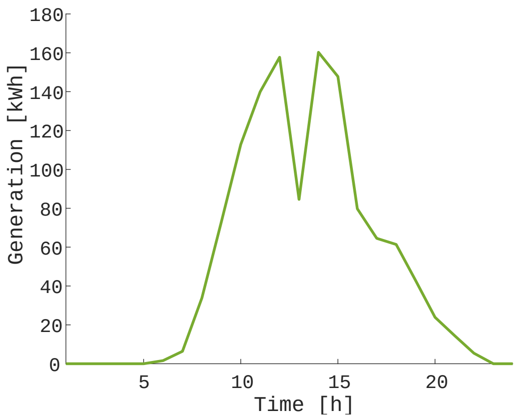


Figure 2.3 – Example of opposed internal and external prices (case 3).



(a) Price trends



(b) Generation

Figure 2.4 – Example of price computation for case 4.

2.3.3 Microgrid operation: management of energy exchanges and cash-flows computation

The IMG Operation (IMGOP) is the management of the energy exchanges of each consumer/prosumer participating to the IMG. The IMGOP is performed by the MGEM for each hour of each day. The main assumption of this operation is that all the prosumers self-consume a maximum of their own generation in priority. After this first step, three cases can be observed:

- The prosumer s becomes a consumer (or purchaser) if its own generation is lower than its load ($p_{s,h} < l_{s,h}$). The remaining load of s is denoted $\lambda_{s,h}$ and is computed by the difference between the load and the generation ($\lambda_{s,h} = l_{s,h} - p_{s,h}$);
- The prosumer s becomes a producer (or seller) if its own generation is higher than its load ($p_{s,h} > l_{s,h}$). The excess of generation, denoted $g_{s,h}$, is therefore computed by the difference between its generation and the load ($g_{s,h} = p_{s,h} - l_{s,h}$);
- The prosumer s is neutral for the exchanges if its own generation is strictly equal to its load ($p_{s,h} = l_{s,h}$).

Each stakeholder s communicates its status of producer or consumer to the MGEM as well as the amount of electricity to sell $g_{s,h}$ (its excess of generation $g_{s,h} = p_{s,h} - l_{s,h}$ for a producer and $g_{s,h} = 0$ for a consumer) or to purchase $\lambda_{s,h}$ (the remaining load $\lambda_{s,h} = l_{s,h} - p_{s,h}$ for a prosumer and the total load $\lambda_{s,h} = l_{s,h}$ for a consumer). The MGEM defines for each hour the total electricity to be sold and to be consumed. If the IMG is composed of S stakeholders, for each hour h, the total load $L_{tot,h}$ and the total excess of generation $G_{tot,h}$ are defined as:

$$L_{tot,h} = \sum_{s=1}^{s=S} \lambda_{s,h} \quad , \quad G_{tot,h} = \sum_{s=1}^{s=S} g_{s,h} \tag{2.7}$$

The next step is to define for each stakeholder, the quantity of electricity to buy or sell at each hour and at which price (outside or inside price). For each of them, a short-term hourly cash-flow $\Delta\rho^{ST}_{s,h}$ is increased by their hourly incomes and decreased by their hourly expenses defined according to the three following cases. For a neutral prosumer, given that there is no exchange of electricity, its short-term hourly cash-flow is equal to zero. Note that for prosumers, the cash-flow has to be increased by $p_{s,h} \times \pi_{GC}$, linked to the GCs for each produced MWh.

CASE 1: If $L_{tot,h} > G_{tot,h}$, all the generation is sold inside the IMG (peer-to-IMG exchanges). A seller can therefore value its excess of generation at the hourly inside price $\pi_{in,s,h}$ (2.9). Regarding the IMG consumers, they purchase a part of their electricity need $X_{N,h}$ (see (2.8)) inside the microgrid proportionally against the total load covered by the total generation. The remaining electricity need comes from the DN (through a supplier). The hourly cash-flow value of a consumer is therefore computed by (2.10). The MGEM earns a fee corresponding to each of those exchanges, as computed by (2.11).

$$X_{s,h} = \frac{G_{tot,h}}{L_{tot,h}} \times \lambda_{s,h} \tag{2.8}$$

$$\begin{aligned} & \textbf{if } s = seller \\ \Delta\rho^{ST}_{s,h} = \quad & g_{s,h} \times (\pi_{in,s,h} - \pi^{fee}_{in,s,h}) - \pi^{met}_{in} - \pi^{met}_{out} \end{aligned} \tag{2.9}$$

$$\begin{aligned} & \textbf{if } s = purchaser \\ \Delta\rho^{ST}_{s,h} = \quad & - X_{s,h} \times (\pi_{in,p,h} + \pi^{fee}_{in,p,h} + \pi^{dso}_{in,p,h}) \\ & - (\lambda_{s,h} - X_{s,h}) \times (\pi_{out,p,h} + \pi^{fee,d}_{out,p} + \pi^{fee,t}_{out,p,h} + \pi^{taxes}_{out,p} + \pi^{new}_{out,p}) \\ & - \pi^{met}_{in} - \pi^{met}_{out} \end{aligned} \tag{2.10}$$

$$\begin{aligned} & \textbf{if } s = MGEM \\ \Delta\rho^{ST}_{s,h} = \quad & \pi^{fee,d}_{out,p,h} \times \sum_{s=1}^{s=S} (\lambda_{s,h} - X_{s,h}) \\ & + \pi^{fee}_{in,s,h} \times \sum_{s=1}^{s=S} g_{s,h} + \pi^{fee}_{in,p,h} \times \sum_{s=1}^{s=S} X_{s,h} \\ & + (S-1) \times (\pi^{met}_{in} + \pi^{met}_{out}) \end{aligned} \tag{2.11}$$

CASE 2: If $L_{tot,h} < G_{tot,h}$, the load of each consumer can be fully covered by the total generation of the IMG. Consumers can purchase all their electricity needs inside the microgrid (2.13). The excess of generation of each prosumer, computed proportionally against the total consumption (2.12), is sold to a supplier. Its hourly cash-flow value is therefore computed by (2.14). The benefits for the MGEM are computed as above, taking into account the selling of electricity (instead of the purchasing) to the network (see 2.15).

$$Z_{s,h} = \frac{L_{tot,h}}{G_{tot,h}} \times g_{s,h} \tag{2.12}$$

$$\begin{aligned} & \textbf{if } s = purchaser \\ \Delta\rho^{ST}_{s,h} = \quad & -\lambda_{s,h} \times (\pi_{in,p,h} + \pi^{fee}_{in,p,h} + \pi^{dso}_{in,p,h}) - \pi^{met}_{in} - \pi^{met}_{out} \end{aligned} \tag{2.13}$$

$$\begin{aligned} & \textbf{if } s = seller \\ \Delta\rho^{ST}_{s,h} = \quad & Z_{s,h} \times (\pi_{in,s,h} - \pi^{fee}_{in,s,h}) \\ & + (g_{s,h} - Z_{s,h}) \times (\pi_{out,s,h} - \pi^{fee,d}_{out,s,h}) - \pi^{met}_{in} - \pi^{met}_{out} \end{aligned} \tag{2.14}$$

$$\begin{aligned} & \textbf{if } s = MGEM \\ \Delta\rho^{ST}_{s,h} = \quad & \pi^{fee,d}_{out,s,h} \times \sum_{s=1}^{s=S} (g_{s,h} - Z_{s,h}) \\ & + \pi^{fee}_{in,s,h} \times \sum_{s=1}^{s=S} Z_{s,h} + \pi^{fee}_{in,p,h} \times \sum_{s=1}^{s=S} \lambda_{s,h} \\ & + (S-1) \times (\pi^{met}_{in} + \pi^{met}_{out}) \end{aligned} \tag{2.15}$$

CASE 3: If $L_{tot,h} = G_{tot,h}$, the load of all the consumers is covered by the total generation of the IMG. Each consumer can sell its need inside the microgrid (2.16). Each producer can also sell its excess of electricity inside the microgrid (2.17). The manager cash-flow is computed by the earnings linked to internal exchanges (2.18).

$$\begin{aligned} & \textbf{if } s = purchaser \\ \Delta\rho^{ST}_{s,h} = \quad & -\lambda_{s,h} \times (\pi_{in,p,h} + \pi^{fee}_{in,p,h} + \pi^{dso}_{in,p,h}) - \pi^{met}_{in} - \pi^{met}_{out} \end{aligned} \tag{2.16}$$

$$\begin{aligned} & \textbf{if } s = seller \\ \Delta\rho^{ST}_{s,h} = \quad & g_{s,h} \times (\pi_{in,s,h} - \pi^{fee}_{in,s,h}) - \pi^{met}_{in} - \pi^{met}_{out} \end{aligned} \tag{2.17}$$

$$\begin{aligned} & \textbf{if } s = MGEM \\ \Delta\rho^{ST}_{s,h} = \quad & \pi^{fee}_{in,s,h} \times \sum_{s=1}^{s=S} g_{s,h} + \pi^{fee}_{in,p,h} \times \sum_{s=1}^{s=S} \lambda_{s,h} \\ & + (S-1) \times (\pi^{met}_{in} + \pi^{met}_{out}) \end{aligned} \tag{2.18}$$

Regarding the DSO, its hourly revenues are also denoted $\Delta\rho_{s,h}^{ST}$ and always computed in the same way. Indeed, they are composed of three terms: a part linked to the electricity taken on the DN (fee $\pi_{out,p,h}^{fee,d}$), added to the part linked to the electricity sent on the DN by the IMG ($\pi_{out,s,h}^{fee,d}$) and added to the part linked to the energy exchanges inside the IMG to compensate its losses because of the decrease of the exchanges with the DN ($\pi_{in,p,h}^{dso}$). All those terms linked to the exchanges of energy are added to the ones linked to the metering costs (π_{out}^{met}).

Finally, if the IEO invests in RESs for its own industrial estate, it could be taken into account as a classical producer in the IMG operation.

2.4 Multi-objective and multi-time horizon challenges of the planning tool

The next challenge of the planning tool rests on the management of the stakeholders decisions. Indeed, in order to achieve their goals, some possible actions have previously been presented such as investing in RESs, investing in ESSs, performing LM or adapting the pricing. For some of the actions, the decisions have to be taken over the long-term time horizon such as for investments. For other ones, the decisions have to be taken daily such as for LM. As the possible actions can be taken over different time scales, the problem is said *multi-time horizon*. On the other hand, as the goals of the different kinds of stakeholder are also different, the problem is said *multi-objective*.

Before going deeper in details with the methodologies linked to the long-term decisions and the Short-Term Energy Management (STEM), let us focus on the chosen methodology to solve the multi-objective problem as well as its adaptation for the different time scales: Game Theory.

2.4.1 Game theory: definitions and presentation of normal and extensive games

Game Theory is a concept which allows to describe and analyse the dealings between different agents who have to take decisions to fulfil their own objectives. It uses interaction between those agents in order to optimise their respective objectives.

Game Theory is based on the theory of the rational choice defined as: *"The action chosen by a decision-maker is at least as good, according to its preferences, as all the other actions available"* [82]. Mathematically, it means that if a and b are two possible decisions for a decision-maker and $f(a)$ and $f(b)$ the utility function attached to a and b, respectively:

$$f(a) > f(b) \quad \text{if and only if the decision maker perfers } a \text{ to } b \tag{2.19}$$

In a generalised way, a game with N-players (decisions makers) is defined by [82]:

- A set of actions $A_i = (a_{i1}, ..., a_{im_i})$ for each player $i = 1, ..., S$ (with m_i the number of actions available for that player). A profile of actions is defined as $a = (a_1, ..., a_N) \in A = A_1 \times ... \times A_N$ where, *e.g.*, a_1 denotes a particular action for the first player among its set of actions A_1.

- An utility function $u_i : A_i \rightarrow \Re$ for each player i, which represents the preferences of the player i. At each profile of actions a is attached an utility function $u = (u_1(a), ..., u_N(a))$. For a player i, if the value attached to action a_{i1} is higher than the value attached to action a_{i2}, this means that he prefers action a_{i1}.

In game theory, the cardinal utility has to be distinguished from the ordinal utility. The cardinal utility implies that the value considered has its importance and their comparison indicates the preference degree of an action compared to another one. The ordinal utilities only describe the preference of one action compared to another one, *i.e.* the values do not quantify this preference and an action is preferable as long as its utility is higher than the utility of another action. Such a game is said *ordinal game* and the utility function is said *payoff*.

At this stage, different kinds of game regarding the information knowledge can already be distinguished [53]:

- The perfect or imperfect information games: in perfect games, all players know the decisions of the previous players, the decisions are not taken simultaneously. In imperfect games, decisions are taken simultaneously, which implies that the players do not know the choice of the other ones;
- Complete and incomplete information games: complete games are deterministic and incomplete games include a part of uncertainties (payoffs or actions can include some probabilities);
- Symmetric and asymmetric information games: in symmetric games, all players have the same decisions set and the same preferences.

One way to solve a game is to find what is called a *Nash equilibrium*, *i.e.*, among all the possibilities of actions profiles, the one which will best satisfy the N players. 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 a stable one, *i.e.* 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 [82]: 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 other profile denoted (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^*:

$$u_i(a^*) \geq u_i(a_i, a^*_{-i}) \tag{2.20}$$

To illustrate the concept of Nash equilibrium, let us consider a simple example of a game with 2 players and the most common form of game, which is the *normal-form game* (which is also called strategic game). In such a game, the notion of *strategies* can also be used for the profile of actions. A normal-form game with two players is characterised by a table in which rows are the possible actions of the first player and columns are the possible actions of the second player. A payoff function (ordinal utility function) representing the preferences of each player for those choices (strategies) is attached to each case of the table (as illustrated in Fig. 2.5). The game is with imperfect information (*i.e.* simultaneous moves), with incomplete information and asymmetric. The computation of the Nash Equilibrium as explained above is possible with this kind of game. For this example, the Nash equilibrium is the combination of actions (Action b, Action d). Indeed, for player 1, Action b is always better than Action a (blue digits). For player 2, Action d is also always better than Action c (green digits). Finally, the equilibrium is the case preferred by both players (red case)

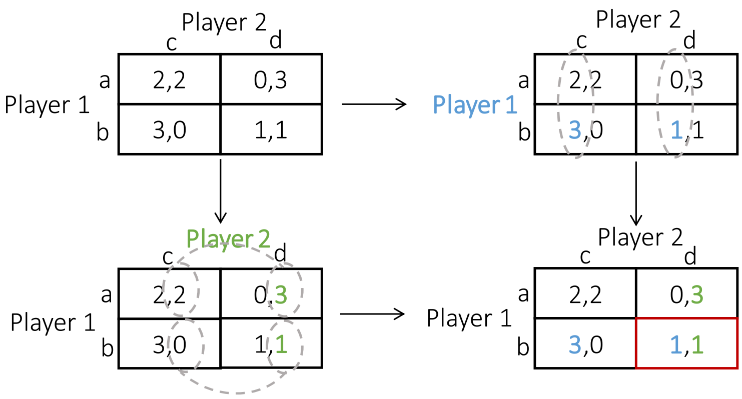


Figure 2.5 – Representation of an normal-form game for 2 players with 2 actions.

Another common way to represent games is to use the *extensive-form representation*. The main characteristic of an extensive game is the possibility to describe the succession in the decision-making process of the N players by a tree structure (Fig. 2.6). In addition to the previous definitions, the following specific characteristics must be considered [82]:

- A finite set of nodes ω which forms the tree structure including the set of terminal nodes τ. At each node (except those within τ) is attached a player i who can choose between actions among its set of actions A_i;
- A set of payoff profiles $u : \tau \longrightarrow \Re$ assigning payoff for the player i at each corresponding terminal node τ.

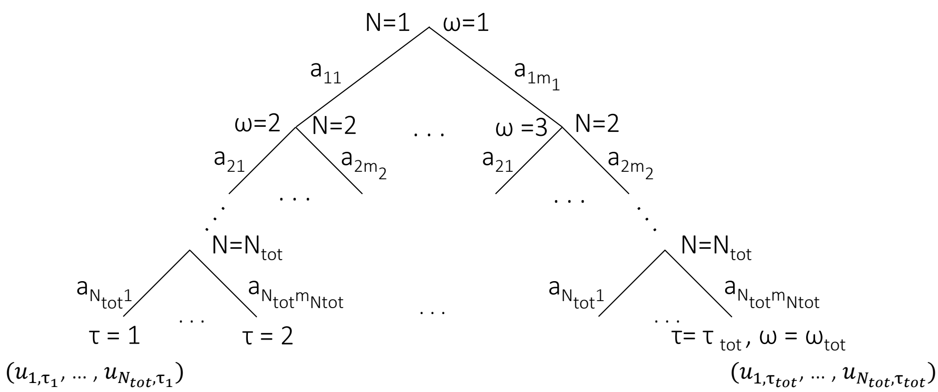


Figure 2.6 – Representation of a general extensive game.

An extensive game can also be with perfect or imperfect information. In the first case, a player knows the actions of the previous players when it has to choose its own action. In the second case, the player is not informed of the previously chosen actions. In order to solve those games, the tree structure can be transformed in a table [84] and, therefore, the Nash equilibrium method can be used to find the equilibrium. Fig. 2.7 illustrates the conversion of an imperfect extensive game to a normal-form game for a game with two players and two actions.

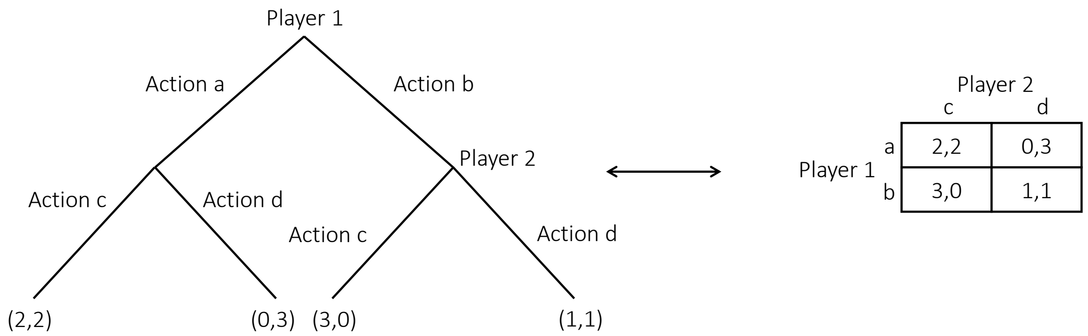


Figure 2.7 – Transformation of an extensive game to a normal game.

However, in the case of perfect information, the number of possible strategies (which are the plans of actions in each situation) for each player is larger because there is a dependence with those of the previous players. Therefore, the table is more complicated to establish and has larger dimensions. For the extensive game with perfect information, other methods of solving should be considered as, *e.g.*, the Backward induction method [83].

Note that there exist a lot of categories of games in the literature [82] used to solve different kinds of problem. In the basic normal form game as illustrated above, the decisions are taken individually and the game is said *non-cooperative*. Other kinds of games allow the players to form groups, called coalitions, to take their decisions. Some games may be played several times or infinitely, they are then called repeated games. On another hand, there also exist other ways to solve the games: for example, mixed-strategies can be use to include a probability part in the found solution. Lots of games and solving methodologies are presented in [82], the interested reader can refer to it. Some of them are presented later in this manuscript (see chapter 4). The remaining of this chapter focuses on the application of normal and extensive form games for the decision-making problem linked to the planning tool developed in this thesis.

2.4.2 Long-term and short-term decisions: co-management of games

In this planning tool, the use of Game Theory seems therefore appropriate in order to take into account the different stakeholders of the IMG, *i.e.* the DSO, the MGEM, all prosumers and consumers and the IEO. Indeed, their objectives previously defined in section 2.2 are various and even sometimes conflicting, which means that the proper planning of the IMG will be obtained by trying to satisfy at best each stakeholder. The particularity of the problem is that, to fulfil at best the objectives of all stakeholders, different kinds of decisions can be taken namely, Long-Term (LT) and Short-Term (ST) decisions.

Indeed, among the possible actions of all the stakeholders listed, some of them have to be realised at a long-term time horizon and others can not be predicted for a long-time in advance and have to be decided at a short-term time horizon according to the generation and consumption profiles. As presented in Tab. 2.1, the MGEM can decide, over the long-term to adopt different levels of pricing in the IMG in order to define an energetic policy. The intervention of the IEO in the electricity pricing or in the investment costs (everything is gathered under the term of *financial aids*) can also be decided for the long-term time horizon.

	Long-term decisions	Short-term decisions
MGEM	pricing levels	daily IMG pricing trend
IEO	financial aids invest in RESs, ESSs	/
Consumer	invest in RESs, ESSs	peak shaving
Prosumer	invest in RESs, ESSs	fit load to generation

Table 2.1 – Long-term and short-term decisions repartition.

Regarding the consumers/prosumers, the investments in RESs and ESSs have to be realised in a long-term perspective. Indeed some companies may be reluctant to make investments which are amortised 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 long-term planning tool is therefore to study the profitability of such investments considering a proper STEM inside an IMG and taking into account the decisions of all the other consumers/prosumers participating to the IMG. The long-term investment decision is taken initially by each stakeholder s ans its cost is considered with a negative cash-flow, denoted ρ_s^{LT}.

Therefore, each LT possible decision is an action in a LT extensive game, solved only once and the application of game theory to the described LT planning problem seems appropriate:

- Player = stakeholders (prosumers, consumers, DSO, IEO and MGEM);
- Actions = investments, LT pricing levels and financial aids.

Everything relative to the electricity exchanges has to be managed at a short-term time horizon. The basic STEM includes the IMG operation and the choice, for the MGEM, between the different daily pricing trends inside the IMG. Each case is a possible action in the ST game. Additional decisions linked to LM can be added for the other stakeholders: peak shaving for the consumers and increasing self-consumption by fitting load to generation for the prosumers (see section 2.4.3). Note that, if storage or electric vehicles are considered in the planning tool, the STEM could also include their presence in its process.

Therefore, each ST possible decision is an action in a ST extensive game, daily solved over the entire planning horizon:

- Player = stakeholders (prosumers, consumers and MGEM);
- Actions = LM decisions and daily pricing.

The implemented methodology must then be thought in order to join the LT game and all the ST games. For that purpose, as shown in Fig. 2.8, the LT extensive game is established to consider long-term decisions. Then, for each final node $i = 1, ..., N_{LT}$ of this first game, the ST extensive game is run to consider the short-term decisions in a loop over the planning horizon Y_{tot}.

Another feature of this game application is the way of computing the utility functions. Regarding the ST extensive game, the utility attached to each terminal node of the ST extensive

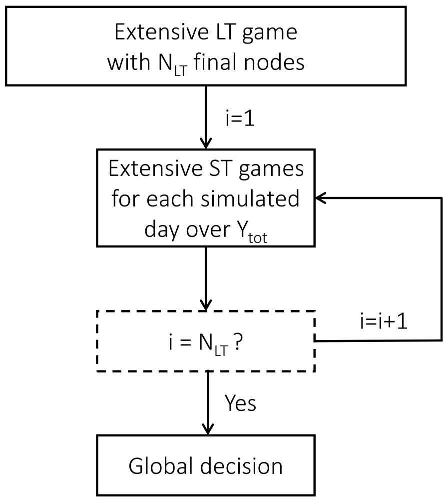


Figure 2.8 – Combination of LT and ST games.

game is either the cash-flow resulting from the IMG operation (for each stakeholder) or a payoff attached to these cash-flow values according to the preferences of the stakeholder:

- Minimum payoff for the most to pay in case of negative cash-flow value or the less to receive in case of positive cash-flow value;
- Maximum payoff for the less to pay in case of negative cash-flow value or the most to receive in case of positive cash-flow value.

Such an ordinal game can be said *ordinal potential game* if there is a potential function F that is such that [85], according to the same notations as previously:

$$u_i(a^*) - u_i(a_i, a_{-i}) > 0 \quad \Leftrightarrow \quad F(a^*) - F(a_i, a_{-i}) > 0 \tag{2.21}$$

The potential function can be defined by the rank value associated to each strategy a^* and measured by counting the number of other strategies/actions profiles $a \neq a^*$ that are leading to a^* without decreasing the payoff amount. This is called a *non-deterioring path from a to* a^* and denoted $a \mapsto a^*$ [85]. Therefore, the rank function can be defined as:

$$r(a^*) = \sum_{a \in A} 1 \times (a \mapsto a^*) \tag{2.22}$$

with $1 \times (a \mapsto a^*) = 1$ if $a \mapsto a^*$ and $1 \times (a \mapsto a^*) = 0$ otherwise.

For more clarity, let us take the previous example and compute the $r(a^*)$ function as a potential function of the game. The methodology to compute the equilibrium is, as also suggested in [86], an *adjustment process*. To build the rank function, we need to observe, for each player at his turn and for each strategy, which other strategy can deviate from the affected one and so on. Fig. 2.9 shows the principle with the previous example of strategic game with payoffs matrix. As observed in the small table of Fig. 2.9.b, the second player will prefer decision d to decision c and the first player will prefer decision b to decision c. Therefore, the rank associated to the strategy bd is 3. In Fig. 2.9.c, the potential function replaces the payoff matrix in the game. Note that the maximum rank value corresponds to the Nash equilibrium of the game.

Player 1 \ Player 2	c	d
a	2,2	0,3
b	3,0	1,1

(a) Payoff matrix

	No deterioring path from	Rank
ac	/	0
ad	ac	1
bc	ac	1
bd	bc , ad , ac	3

(b) Rank computation

Player 1 \ Player 2	c	d
a	0	1
b	1	3

(c) Potential function

Figure 2.9 – From payoff matrix of a strategic game to its potential function.

This last property is the advantage of such a game because, for an ordinal potential game, the presence of a Nash equilibrium is ensured. To cite [86]: *The maximum of a potential function for a game is a pure Nash equilibrium*. All the definitions, theorems and lemmas linked to these properties can be found in [85] and [86].

Getting back to our application, each ST and then, LT node, will be attached to different payoff values because each decision to take will change the amount of energy exchanged and/or the electricity price considered, leading to cash-flows at least a little bit different from one node to another. Therefore, **the considered games in the tool are extensive imperfect games that can be brought to normal-form strategic games. Moreover, those games are also ordinal potential games and consequently have at least one Nash equilibrium.**

2.4.3 Short-term energy management including load management optimisation

This section is dedicated to the integration of the LM optimisation in the STEM. For that purpose, let us first develop the general principle of LM optimisation for both the consumers and the prosumers and then detail its integration in the ST decision game [87], [88].

Among all the industrial companies, some of them have a daily load profile which can usually be divided into two parts: the base load and the process load. The base loads are the ones that are not flexible and that can consequently not be shifted. Those fixed loads are related to the welfare of the workers and are always used by them, *e.g.*, the lights, the heating and the computers. The process loads are the ones linked to some industrial activities. The main characteristic of industrial companies is that their process loads are subject to contracts and deadlines linked to their activities. Therefore, according to the company possibilities and willingness, these loads are more or less shiftable. The load profile of a company c, L_c, and its decomposition for each hour h of a day are respectively expressed by (2.23) and (2.24).

$$L_c = [l_{c,1} \quad \dots \quad l_{c,24}] \tag{2.23}$$

$$l_{c,h} = l_{b,c,h} + l_{pr,c,h} \tag{2.24}$$

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 concerned industrial company c, the two following vectors can therefore be defined:

$$L_{b,c} = [l_{b,c,1} \quad \dots \quad l_{b,c,13}] \tag{2.25}$$

$$L_{pr,c} = [l_{pr,c,1} \quad \dots \quad l_{pr,c,13}] \tag{2.26}$$

LM can only be processed on $L_{pr,c}$ (with some constraints) whereas $L_{b,c}$ can not be changed. This means that $L_{pr,c}$ can be arranged in order to provide the desired load profile which is different according to the consumer or prosumer status of the company and if the LM optimisation is performed individually, *i.e.* decentralised (DLM), or globally, *i.e.* centralised (CLM). All possibilities are formulated as a Mixed Integer Linear Programming (MILP) optimisation problem, with x the integer vector with binary decisions to activate shiftable process loads at each hour h. Moreover, those optimisation problems take into account a grid price weight for each hour during which LM is applicable, $\Pi_{LM} = [\pi_{LM,1}, ..., \pi_{LM,13}]$, corresponding to the normalised electricity purchasing price compared to its average between 6am and 6pm.

Decentralised LM

The DLM is performed individually, by each concerned company c, to satisfy its own objective, as presented in Fig. 2.10. As the MGEM firstly predicts the load of the companies (based on historical data initially provided to him), he communicates the predicted load profile to each company (orange arrow) for the next day. Each company sends back to the MGEM the load profile with possible LM adaptation(s) (blue arrow). In the STEM, LM decisions are represented in the daily extensive game. In the DLM methodology, each concerned company is a player of the game with two actions: do LM or keep initial load profile. The game is solved by the MGEM in order to predict which concerned company has to apply LM. Then the MGEM informs the company if it has to keep its initial load profile or to apply LM (green arrow).

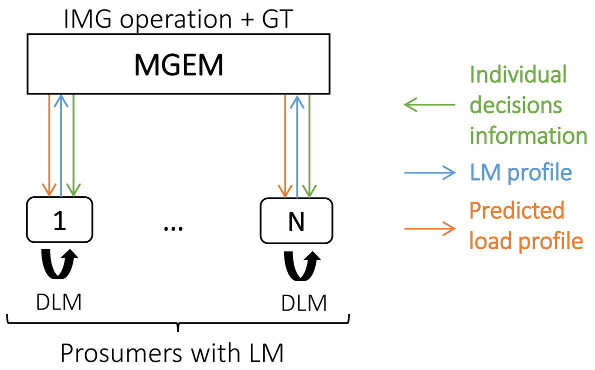


Figure 2.10 – DLM principle.

Regarding **the consumers**, as presented in the section dedicated to the pricing, a part of the electricity cost is linked to their peak of consumption over the year. This part is a significant one, which can therefore represent a huge part of its electricity bill. With LM, his main objective is to decrease the peak of consumption, *i.e.* to move some process in order to smooth its consumption profile around its average consumption of the day, $l_{average,c}$, computed as:

$$l_{av,c} = \frac{\sum_{h=1}^{h=13} l_{c,h}}{13} \tag{2.27}$$

The optimisation problem resulting from this kind of LM, called DLM_{cons}, can be expressed as follows, where $h' \in [1 \quad \dots \quad 13]$:

$$min \sum_{h=1}^{h=13} [|l_{b,c,h} + l_{pr,c,h'} - l_{av,c}| \times \pi_{LM,h)}]^T \times x \tag{2.28}$$

After the optimisation, each process is no longer necessarily attached to the same hour, which means that h' could be the same or different from h. For each company c, the vectors of (2.28) are composed of the number of hours (13) times the number of processes (13) elements.

Fig. 2.11 shows an application of DLM_{cons}. The new consumption profile (orange) clearly better matches the average load (dashed grey) than the initial one (grey). Both peaks of consumption are shaved and the important hourly variations are decreased. In order to numerically observe the smoothing of the consumption profile, the standard deviation between the initial profile and the average load as well as the one between the new profile and the average load have been computed and are 23.11 and 4.98, respectively, which testifies the proper implementation of DLM_{cons}.

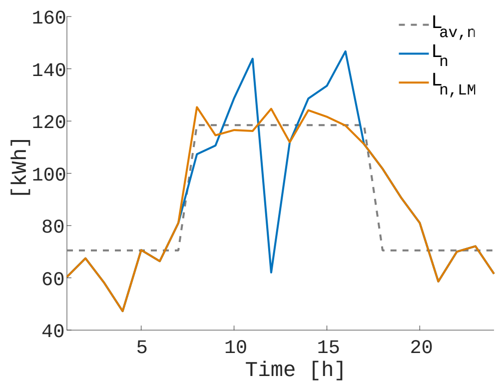


Figure 2.11 – Example of application of DLM_{cons}.

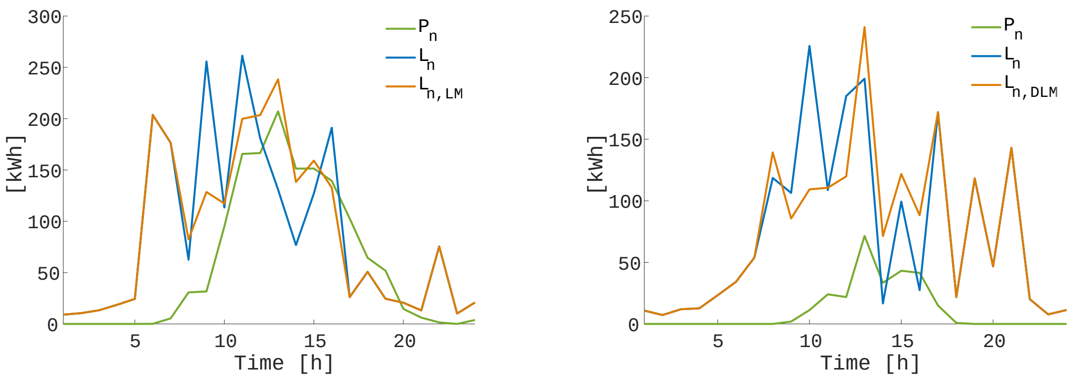
The main goal of **the prosumers** is to take advantage of their own generation, in order to make their PV installation more profitable. LM can therefore be used to improve its self-consumption rate by decreasing the difference between his consumption and generation profiles. Indeed, the electricity produced by the PV installation of a company c, P_c, can also be decomposed in a vector of 13 components, corresponding to the working hours of the day:

$$P_c = [p_{c,1} \quad \dots \quad p_{c,13}] \tag{2.29}$$

The optimisation problem resulting from this kind of LM, called DLM_{pros}, can be expressed as follows, with $h' \in [1 \quad \dots \quad 13]$:

$$\min_x \sum_{h=1}^{h=13} [|l_{b,c,h} + l_{pr,c,h'} - p_{c,h}| \times \pi_{LM,h}]^T \times x \tag{2.30}$$

Two applications of DLM_{pros} are illustrated in Fig. 2.12: the left figure is a summer day and the right one a winter day. DLM_{pros} is applied in the same way but, given the difference between both generation profiles, the computed benefits are different. In summer, the load profile better matches the generation profile. Besides, the self-consumption rate goes from 79.9% to 92.2%. In winter, without any LM, there are two hours during which the consumption is lower than the generation despite its low level. DLM_{pros} allows to arrange the loads in order to always consume all the available generation.



(a) A summer day

(b) A winter day

Figure 2.12 – DLM_{pros} applications.

For both DLM optimisation problems, each process can occur only once during the corresponding day (with only one process to be operated at each hour).

Centralised LM

The centralised methodology (see Fig. 2.13) refers only to one initial information exchanged between the companies and the MGEM (grey arrow) regarding the constraints for LM and their process ($e.g.$ if some processes have to follow one another, can not be shifted, etc.). After that, all the CLM process is performed by the MGEM during the STEM. The decision of doing CLM or not is then communicated to each concerned company (green arrow). Therefore, the communication needs are reduced compared with the DLM methodologies because the amount and the complexity of information exchanged are lower.

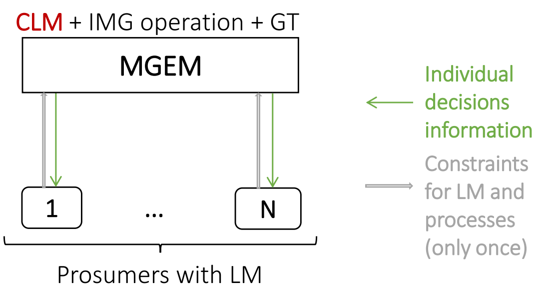


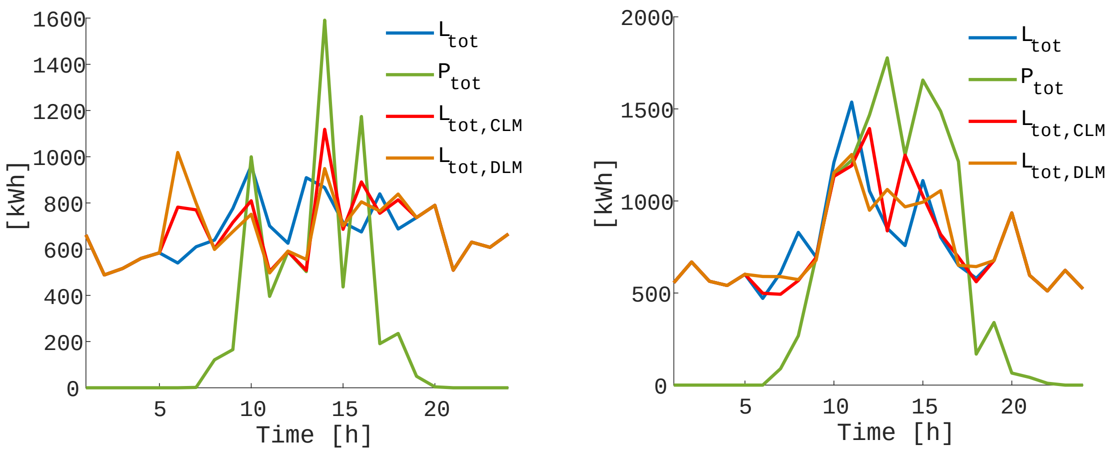
Figure 2.13 – CLM principle.

The formulation of the optimisation problem (2.31) is now unique and takes into account all the companies capable of doing LM ($i.e.$ C_{LM} companies) on the one side and all the other ones on the other side. The dimension of the vector is therefore $13 \times 13^{C_{LM}}$ in order to consider the

13 simulated hours and the combination of the process loads of the C_{LM} concerned companies. Regarding the extensive game attached to the CLM decision, **there are now only two players: the MGEM and all the companies. That means that, after solving the game, all or none of the concerned companies must apply LM**. As for DLM optimisation problems, each process can occur only once with only one process applied by hour for each stakeholder.

$$\min_{x} \sum_{h=1}^{h=13} \left[\left| \sum_{c=1}^{C} l_{b,c,h} - \sum_{c=1}^{C} p_{c,h} + \sum_{c \in C_{LM}} l_{pr,c,h'} \right| \times \pi_{LM,h} \right]^{T} \times x \tag{2.31}$$

In order to observe the difference between DLM and CLM, both optimisations are applied on two different days (Fig. 2.14) for an IMG composed of 6 stakeholders including the MGEM ($C = 5$). Only prosumers 1, 2 and 4 have load profiles which allow to perform the implemented LM ($C_{LM} = 3$). The IMG is connected to the 10.5kV distribution grid. The results are exposed with the decisions taken thanks to a daily extensive game including the LM decisions for prosumers. MGEM decisions are applying fix or variable prices. In these figures, L_{tot} and P_{tot} represent the sum, over the 5 companies, of respectively the loads and the generation profiles.



(a) Day 72 (March)

(b) Day 134 (May)

Figure 2.14 – LM applications and comparison.

For the day 72, the self-consumption rate of the companies as a whole is almost unchanged with DLM (which is only DLM_{pros} in this example) and clearly increased with CLM (80% tot 85%). For both DLM and CLM, a constant price is chosen and CLM leads to a decrease of the IMG costs. With DLM, only companies 1 and 2 have to perform the LM.

For the day 134, the peak of consumption observed at hour 11 is shaved by both CLM and DLM. We can observe that the load profile is smoother with DLM and constant price is chosen by the game equilibrium, leading to lower costs for the IMG than with CLM for which variable price (with the same trend as the external price) is chosen as equilibrium. Note that if a variable price is applied with DLM, CLM becomes more interesting for the IMG. We can therefore conclude that both CLM and DLM are of interest according to the daily load and price profiles.

IMG and companies load peaks computation

Regarding the exchanges with the DN, the peak of consumption is taken into account two times: the first one against the distribution network ($\pi^{peak,d}_{out,p}$) and the second one against the transmission network ($\pi^{peak,t}_{out,p}$). Therefore, the peak of consumption represents an important part of the global purchasing cost.

The use of LM (both DLM or CLM) can reduce the peak of consumption of the IMG as a whole (seen from the DN by the single connection node). For that purpose, the IMG operation includes a new method to compute the peak of consumption of each prosumer/consumer when the peak of the IMG as a whole occurs. The new method of computation is implemented as follows:

1) For each day, the peak of consumption of the microgrid without any LM (first terminal node ($\tau = 1$) of the daily short-term tree), $l^{peak}_{IMG,1}$, is computed by (2.32). The corresponding peak of each stakeholder s for this peak value is denoted $l^{peak}_{s,1}$. A ratio W_s (see (2.33)) is computed in order to obtain the weight of each prosumer/consumer for this global peak.

2) When LM is applied for one prosumer/consumer at least (for each other terminal node $\tau > 1$ of the daily short-term tree), another global peak of consumption, $l^{peak}_{IMG,\tau}$, is computed, with the new profile of hourly loads. In order to keep a global welfare inside the IMG, the targeted load peak of each stakeholder s with LM profile(s), $l^{peak}_{s,\tau}$, is computed according to the ratio of the peak without LM W_s, so that the LM performer(s) is(are) not the only one(s) to take advantage of the IMG operation.

$$l^{peak}_{IMG,1} = max\left(\sum_{s=1}^{s=S} l_{s,h,1}\right) \quad \forall h \in [1, ..., 24] \tag{2.32}$$

$$W_s = \frac{l^{peak}_{s,1}}{l^{peak}_{IMG,1}} \quad \Rightarrow \quad l^{peak}_{s,\tau} = W_s \times l^{peak}_{IMG,\tau} \tag{2.33}$$

As the load peaks of the companies are not necessarily synchronous, this methodology could be advantageous for some companies and penalising for other ones. However, this methodology has been thought is an IMG community idea. Its impact will be observed in the next chapter. Of course, other methodologies could be implemented in the planning tool in order to see their influence on the companies behaviour.

2.5 Conclusion

In a general way, this chapter was dedicated to the explanation of the different challenges of the planning tool development and methodologies applied to face them. Practically, **three main challenging points for the planning of the IMG have been highlighted and solved**:

1) **The inclusion of all stakeholders in the decision-making process:** for that purpose, the use of game theory was proposed to take into account their respective objectives and to find a solution that represents a global welfare for all of them;

2) **The definition of a new regulatory framework** allowing new kinds of electricity exchanges and promoting the IMG concept;

3) **The combination of both the multi-objective and the multi-time scale aspects of the planning problem:** for that purpose, extensive games were adapted in order to co-manage them at both long and short-term time horizons.

In the following chapter, a more specific application of these methodologies to a first version of the planning tool of IMGs will be exposed.

2.6 Chapter publications

This chapter has led to the following publications:

- C. Stevanoni, F. Vallée, Z. De Grève, O. Deblecker and P. Couneson, "Long-Term Planning of Industrial Microgrids", *In Proc. Young Researchers Symposium*, Eindhoven, The Netherlands, May 2016.

- C. Stevanoni, F. Vallée, Z. De Grève and O. Deblecker, "Optimized Decentralized and Centralised Load Management Techniques in Industrial Microgrids", *In proc. International Conference on Electricity Distribution (CIRED) Workshop 2018*, Ljubljana, Slovenia, June 2018.

Chapter 3

Developed tool for small IMGs: principle and application

In the first part of this chapter, the principle of the developed planning tool is described through the explanation of each block of the general flowchart presented in Fig. 3.1. These descriptions gather the previously discussed problems of planning and decision-making, the use of Game Theory and the energy management of the IMG. The first section is devoted to the analysis of the available data including historical load profiles of the IMG companies, generation and price profiles. Then, scenarios, linked to the long-term uncertainties of the planning problem, modelled over 20 years of planning are presented. The specific application of Game Theory for the long-term decisions process and the STEM for this first tool are presented as well as Net Present Value (NPV) objective function. In the second part of this chapter, a numerical application of the tool is presented as well as a complete analysis of the results. This chapter is concluded by a description of the limits and weaknesses of the presented tool. Note that this part of the work has been published in the IEEE Transactions on Smart Grids journal [89].

3.1 General flowchart description

The flowchart presented in Fig. 3.1 represents the structure of the tool. This tool has been implemented in Matlab and is divided into five main parts:

1) The inputs of the tool including historical data and investments possibilities for the concerned companies;

2) The long-term forecasting of the data;

3) The construction of the LT configurations, $i.e.$ the LT extensive game;

4) The STEM;

5) The final decision(s) of investment(s);

In the following of this section, each of these parts is detailed according to its application in this first version of the tool developed in this thesis.

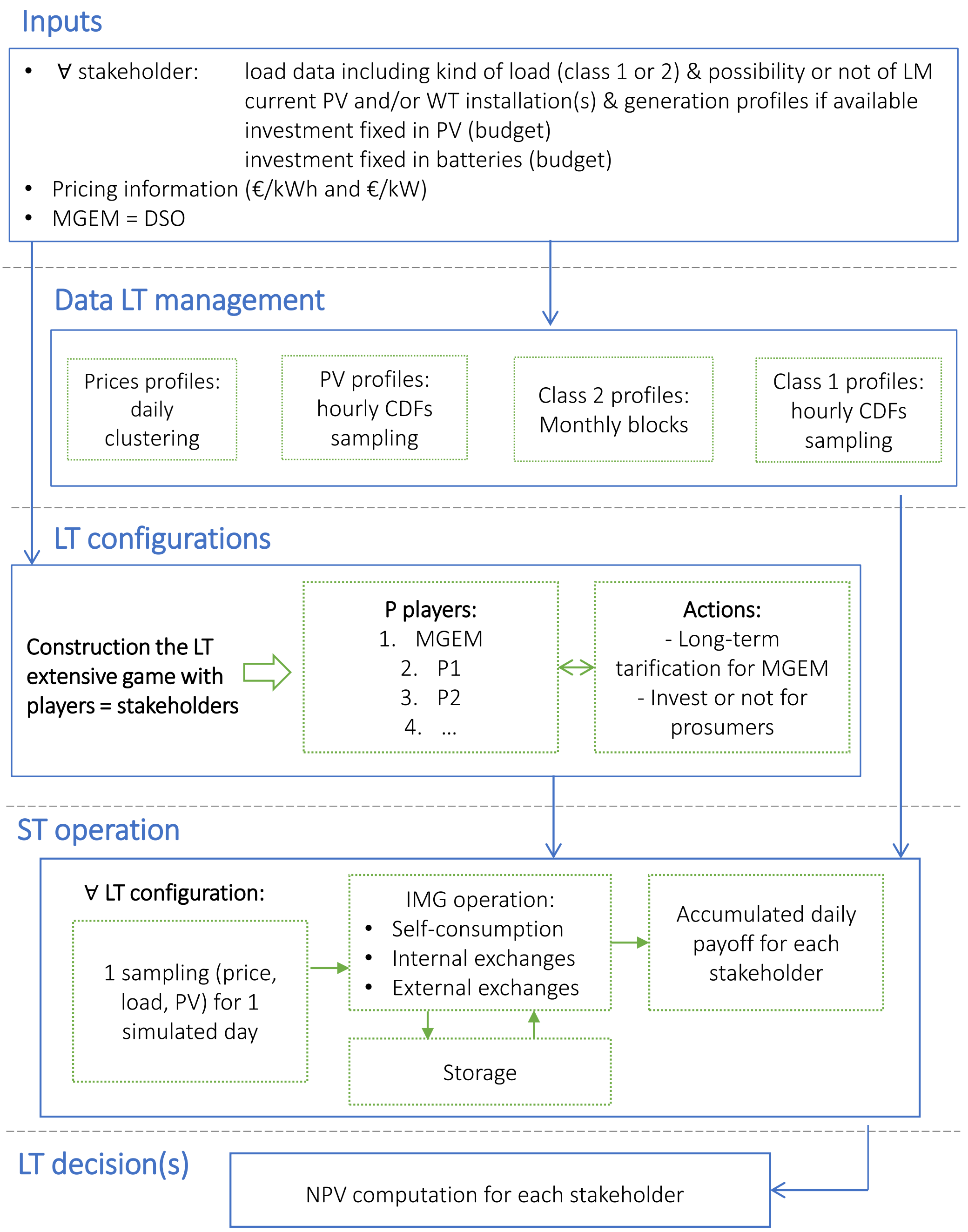


Figure 3.1 – Flowchart of the planning tool for small microgrid.

3.1.1 Inputs of the tool

In order to properly run the tool, some information needs to be provided to the MGEM. The first one is the historical hourly load data of the participating companies. Of course, a confidentiality contract must be established between those companies and the MGEM (who is the only one to know this information). Regarding its load profile, a company also has to inform the MGEM if some LM is practicable or not. Another important information is the consumer or the prosumer status of the company, *i.e.* if the company already has its own RES. If the answer is yes, historical hourly generation data must also be given to the MGEM. Finally, the companies have to inform the MGEM about their possibility (*i.e.* their budget) to invest in new RESs or ESSs.

On the other side, the MGEM must know the historical hourly day-ahead purchasing price of electricity as well as the pricing condition inside the concerned industrial area, *i.e.* the detailed values of each component of the electricity price such as the distribution and transmission costs (energy and power) and the taxes.

In this chapter, the MGEM is imposed to be the DSO. That means that the MGEM must fulfil the objectives of both roles.

3.1.2 Data pre-processing: analysis and long-term modelling

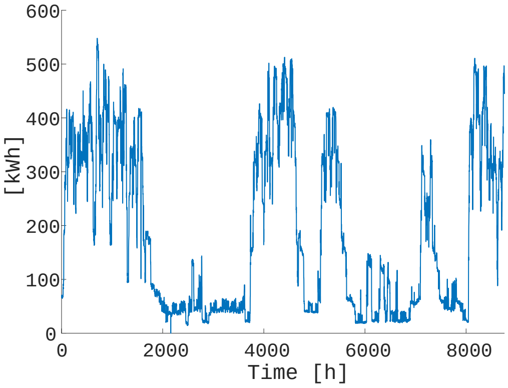
Three types of data are concerned by the long-term forecasting: the load, the generation and the price.

Regarding the load data, different kinds of industrial companies can be part of the IMG. Some of them, that will be said from class 1, are industries. Those companies are characterised by periods of days, weeks or even months (including week-ends) of important consumption, as illustrated in Fig. 3.2a for one year. Those profiles are without any seasonality and daily recurrences.

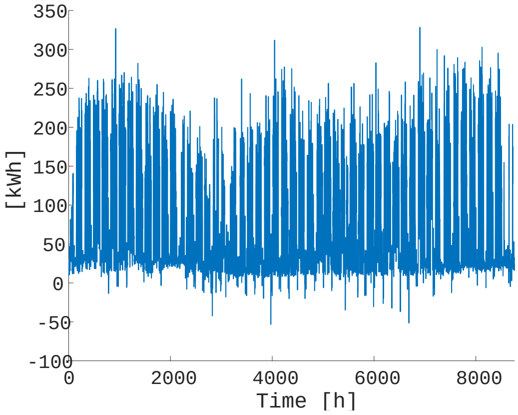
The second class of companies are the offices or workshops. Those companies are characterised by a daily consumption (see Fig. 3.2b, 3.2c and 3.2d). Their periods of high consumption are congruent with the working hours of the business days, as illustrated for one week in Fig. 3.2d. According to the nature of the activities, those profiles can have a higher or lower level of consumption, but the daily aspect is always respected. Moreover, this kind of companies can also be distinguished by a seasonality over the year, which means that the base consumption is slightly higher during winters than summers (Fig. 3.2c). However, for more and more companies, this seasonality is reduced by the use of reversible heat pumps (which cool in summer and warm in winter).

The way of long-term modelling the load data of all companies depends on the company class. Indeed, for the first class, the modelling process is going to be made by monthly blocks (inspired from [90]) and, for the second one, by a daily method using cumulative distribution functions (CDF) (inspired from [91]).

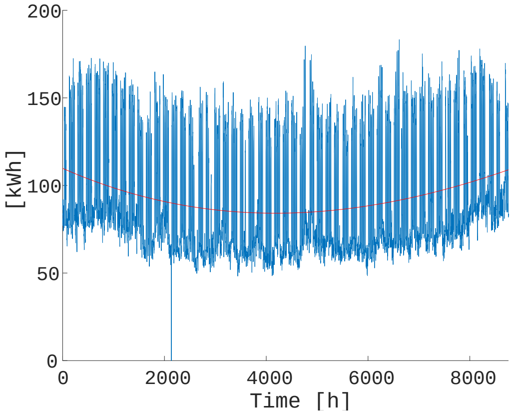
For an industry, the block method consists in dividing each year of available data of the considered industry into monthly blocks (730 hours), as illustrated in Fig. 3.3a. Then, a modelled



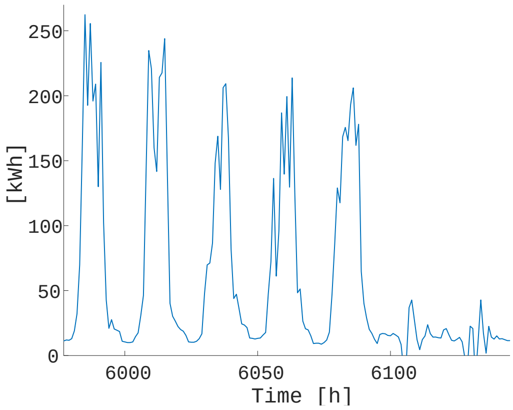
(a) Class 1 industry



(b) Class 2: profile without seasonality

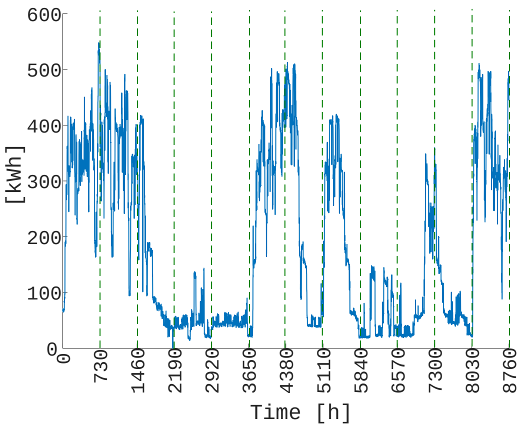


(c) Class 2: profile with seasonality

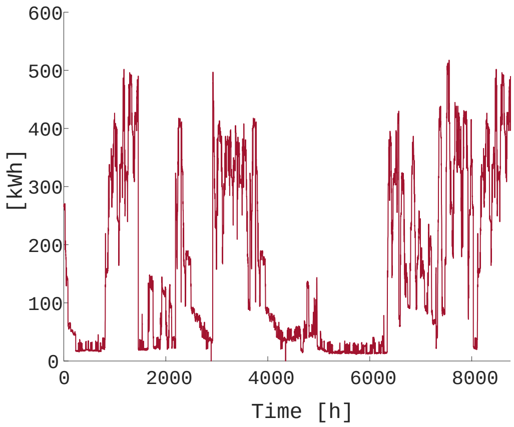


(d) Class 2: week profile

Figure 3.2 – Load profiles examples.



(a) Division of a year of data in 12 block.



(b) New computed profile by 12 randomly chosen blocks.

Figure 3.3 – Block method to model an industry consumption profile.

year is built by 12 randomly chosen blocks sampled on all the available ones (Fig. 3.3b). This method is quite simple but allows to properly represent the activities of the company over the long-term time horizon.

The CDFs method, for a company of class 2, is performed as follows:

- The same days of the week (Monday to Sunday) are gathered among all the years of available data y_d, *i.e.* $52 \times y_d$ daily profiles for each day. From those sorted data, a mean profile is computed for each day. Fig. 3.4 gathers an example of seven daily mean profiles for such a company;

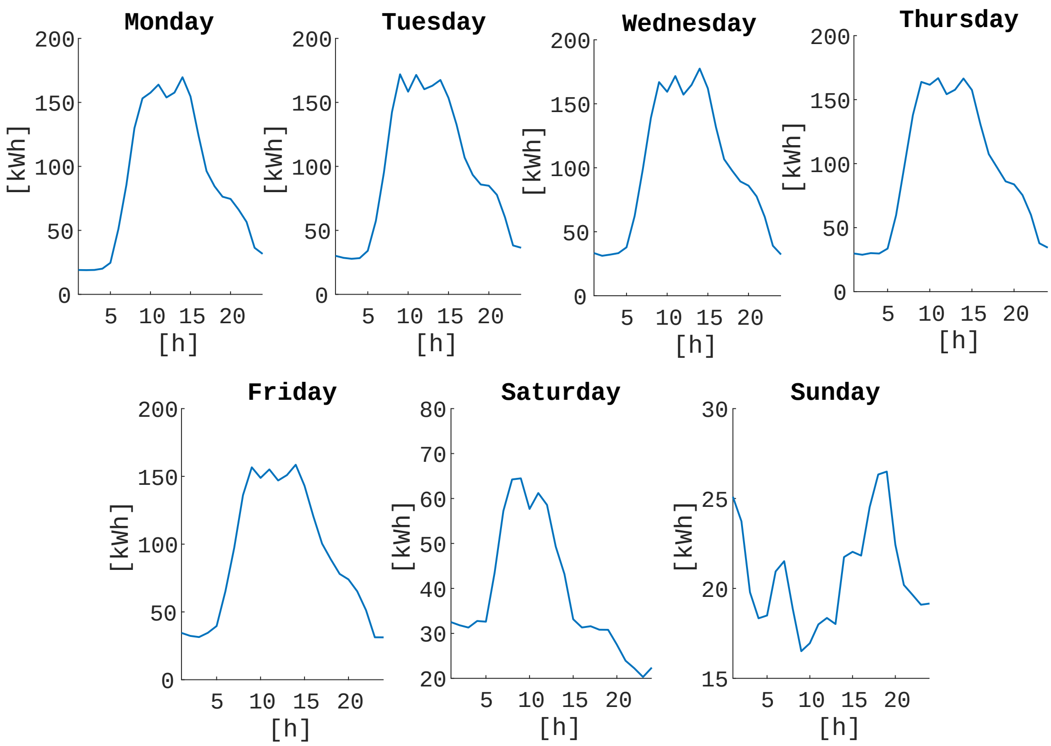
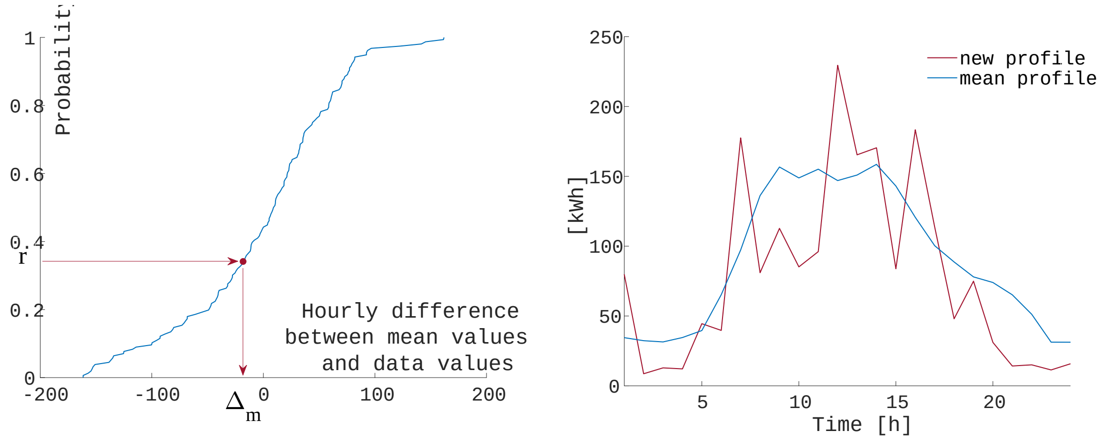


Figure 3.4 – Daily mean profiles for a company from class 2.

- For each hour of the seven days of the week, a CDF is computed by making the difference between the hourly value of the daily mean profile and all corresponding values (for this day) in the available sorted data. Each CDF is therefore built with $52 \times y_d$ data. An example of hourly CDF curve is presented in Fig. 3.5a;

- To model a new hour of a day, a sampling is performed on the corresponding CDF. An uniformly distributed random value *rand* is computed and the corresponding Δ_m is raised by inversion of the considered hourly CDF (as illustrated by red arrows in Fig. 3.5a). The value Δ_m is therefore an hourly difference against the mean profile. This value is added to the corresponding daily mean profile. The process is performed for each hour of the day in order to compute a new daily profile. Fig. 3.5b shows an example of new profile (red) superposed with the corresponding mean profile (blue).

The PV generation profiles are also long-term forecasted with the CDFs methodology given the daily shape of the curve as illustrated in Fig. 3.6. The only difference is that only one general mean profile is computed because distinguishing the days of the week does not make any sense for an uncertain generation profile.



(a) Hourly CDF and sampling principles

(b) New computed daily profile in comparison with the corresponding mean profile

Figure 3.5 – CDFs method to model an office or workshop consumption profile.

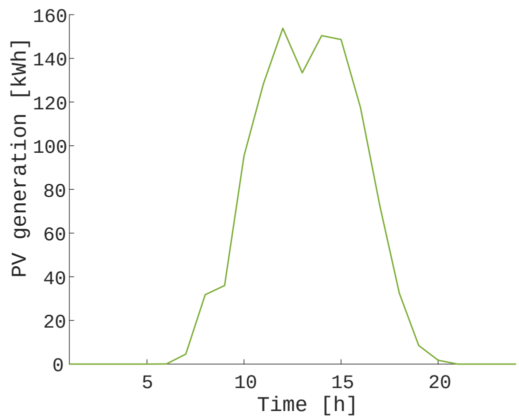


Figure 3.6 – PV generation profile example.

Regarding the electricity price profiles, their are daily sampled among the available data.

In this first planning tool developed, a sampling is realised each day of the 20 years of planning, by making the assumption that 365 × 20 samplings for each hour are sufficient to converge to results that are meaningful.

Scenarios definition

Now that new data profiles can be built over the 20 years of planning, some uncertainties over the long-term must be taken into account. For this specific planning methodology, three main uncertainties have to be taken into account. The first one is the evolution, over the 20 years of planning, of the consumption profiles. Indeed, if the activities of a company are growing, the global consumption of the company increases. However, this growth can be more or less important according to its nature (more industrial processes, more employees, new materials, etc.). Besides, the current progress in smart technologies and energy efficiency could therefore mitigate the increase of the consumption, or even decrease the global consumption (mainly if the activity of the company does not extend).

The second major uncertainty is the evolution of the electricity purchasing and selling prices over the 20 years of planning. Indeed, this evolution is based on the technical and economical evolutions of the generation means (new plants, deterministic generation or not, etc.) and of the grid (investments, reinforcements, etc.). Therefore, the commodity price (currently representing about 30% of the electricity price) is depending on the day-ahead market and the other costs are linked to the distribution and transmission grid fees and the taxes from the state.

Finally, the last uncertainty comes from the evolution of the price of investment in RESs and ESSs. However, currently, the choice of investing in a RES or a ESS is realised initially (at year 0). That means that the cost of those installations is the current one and its evolution has not been taken into account yet.

Regarding the two first uncertainties, they are taken into account through long-term linear evolutions. The first possibility is to remain constant, the second one to increase and the third one to decrease. Increasing and decreasing trends are taken into account through a percentage of 2% by each year. A posteriori, a sensitivity study should be realised in order to observe the influence of the different percentage values. In order to consider the different possible evolutions for both the consumption profiles and the electricity prices, all the combinations of evolutions, called scenarios, are created. Therefore, nine scenarios Ψ_i, where $i = 1, ..., 9$, are defined as:

- Global consumption remains constant:
  - Ψ_1: Prices are constant;
  - Ψ_2: Prices increase by 2% each year;
  - Ψ_3: Prices decrease by 2% each year.
- Global consumption increases by 2% each year:
  - Ψ_4: Prices are constant;
  - Ψ_5: Prices increase by 2% each year;
  - Ψ_6: Prices decrease by 2% each year.
- Global consumption decreases by 2% each year:
  - Ψ_7: Prices are constant;
  - Ψ_8: Prices increase by 2% each year;
  - Ψ_9: Prices decrease by 2% each year.

3.1.3 Long-term investments and configurations

In order to consider PV and ESS installations in a realistic way, their sizing has to be properly computed. The sizing of a new PV system is based on an existing one in the considered industrial estate and takes into account both the peaks of consumption and the peaks of generation over the 20 modelled years of consumption and generation data, respectively. It means that, according to the scenario considered, the installed power for a given company will be different.

Indeed, the installed power will be higher for scenarios with an increase of consumption and lower for scenarios with a decrease of consumption, respectively. The hypothesis of 100% of correlation between the PV installations inside the IMG seems to be realistic given that they are geographically close to each other. It also involves exactly the same orientation (-16° with respect to the south) and inclination (20° with respect to the horizon) than the existing ones. However, the installed power is limited in order to be realistic towards the fact that they are totally decentralised installations with determined and limited geographic areas. The limitation is fixed at 400 kW for those simulations. Note that, in the current regulatory framework, aids are only provided for 250 kW peak power of the installations. New kinds of aids (*e.g.* by the IEO) can therefore be considered in the new regulatory framework established. According to the various information recently known and to information linked to the existing installation, a cost of 1.3 € per installed kW is considered for those simulations.

Regarding the sizing of an ESS, usually, one kWh of storage capacity is installed for one kW of PV installed. This principle is applied in the tool. The pricing of ESS is defined according to the pricing of a power and an energy part, that are $500€/kW$ and $200€/kWh$ installed, respectively.

As described in the previous chapter, game theory is used in order to make the proper long-term choice of investment. For this purpose, a first tree structure is established in order to clearly see the possible combinations of decisions. At each terminal node $\tau_i \in \tau$ of this tree, a payoff function is attached considering the payoff of each stakeholder $S \in S_{tot}$. This payoff is actually the long-term component of the cost objective function ρ_s^{LT} that will be now denoted ρ_{s,τ_i}^{LT} in order to take into account the terminal node that is being considered. An example of long-term tree is presented in Fig. 3.7 for S stakeholders, where $S = DSO + \sum_{i=1}^{i=C} C_i$ and C_i are the concerned companies.

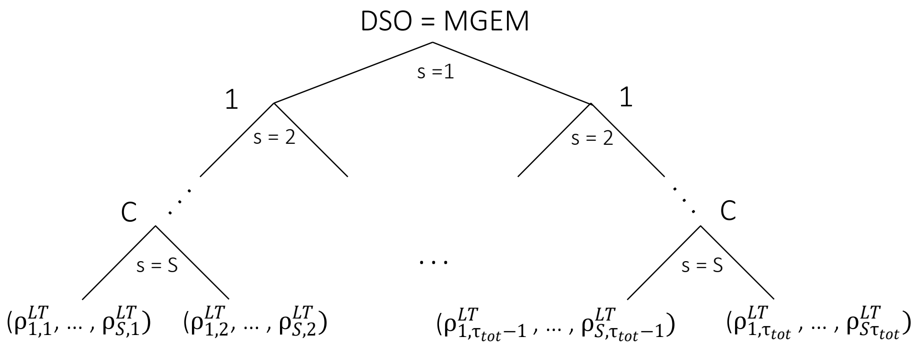


Figure 3.7 – Representation of a long-term extensive tree.

In the current studied strategy, with the DSO as MGEM, the IEO can either provide aids or decide to also invest in RESs or ESSs. However, as previously presented, its benefits linked to the aids are not directly quantified and, therefore, this decision does not appear in the tree. For the second possibility, the IEO becomes a producer (to sell its generation or its stored energy) or a consumer (to store energy) and he is then included in the tree among the C_i.

3.1.4 Short-term energy management

One day is considered as short-term time horizon. In this version of the tool, the short-term management gathers two global operation processes: the LM and the IMG operation. Hence, the daily management method is defined as follows:

- LM optimisation (for the day) is performed by (if DLM) or for (if CLM) each concerned prosumer or consumer. The daily load profiles attached to the actions of each concerned company in the short-term are therefore the one with LM and the initial one;
- If an individual ESS is installed, the concerned company stores as much as possible in its ESS if there is a generation surplus and consume as much as possible from its ESS otherwise. These exchanges with the ESS are limited by the constraints of the batteries linked to the higher and lower limits in terms of storage capacity;
- The MGEM performs the hourly IMG operation (described in the previous chapter) over the 24 hours of the day for each terminal node τ_j;
- After the execution of the IMG operation for each hour of the day, a daily cash-flow $\rho^{ST}_{s,t}$ is attached to each stakeholder s. These cash-flows are computed by (3.1) and (3.2) for the prosumers/consumers and the MGEM, respectively. The cost or the gain linked to the peak of consumption is then taken into account for the purchasers/sellers and the MGEM, respectively. In the following equations, t is the accumulated day over the years ($t = d + (Y-1) \times 365$, where Y is the year ($Y \in [1, ..., Y_{tot}]$) and d is the day of the year ($d \in [1, ..., 365]$), r is the discount rate to consider the actualisation of the short-term cash-flow and l^{peak}_s represents the peak of consumption of the stakeholder s.

  if $s = purchaser \quad or \quad seller$

$$\rho^{ST}_{s,t} = \rho^{ST}_{s,t-1} + \left[\sum_{h=1}^{h=24} \Delta\rho^{ST}_{s,h} - l^{peak}_s \times (\pi^{peak,d}_{out,p}/365 + \pi^{peak,t}_{out,p}/365 + \pi^{peak}_{in,p}) \right] \times \frac{1}{(1+r)^Y} \tag{3.1}$$

  if $s = MGEM$

$$\rho^{ST}_{s,t} = \rho^{ST}_{s,t-1} + \left[\sum_{h=1}^{h=24} \Delta\rho^{ST}_{s,h} + \sum_{s=1}^{N=N_{tot}} l^{peak}_s \times (\pi^{peak,d}_{out,p}/365 + \pi^{peak}_{in,p}) \right] \times \frac{1}{(1+r)^Y} \tag{3.2}$$

- Each stakeholder S is associated with its cumulative daily short-term cash-flow $\rho^{ST}_{s,t}$ for each terminal node τ_j, now denoted ρ^{ST}_{s,t,τ_j} to distinguish each node. Each terminal node of this daily tree is characterised by (see Fig. 3.8):

$$(u_1(\tau_j), ..., u_S(\tau_j)) = (\rho^{ST}_{1,t,\tau_j}, ..., \rho^{ST}_{S,t,\tau_j}) \tag{3.3}$$

- For each day, an equilibrium [82] is computed to define the management policy (in terms of LM and daily pricing) that should be adopted in order to satisfy at best each stakeholder. The short-term cash-flow of the selected terminal node of the daily tree is the initial value for the next day in order to increment the payoffs functions. Note that an industrial company which can not realise LM ($e.g.$ a company from class 1) is also considered in the short-term game but with the only possibility of doing nothing (No). The company cash-flows are also computed and taken into account in the game.

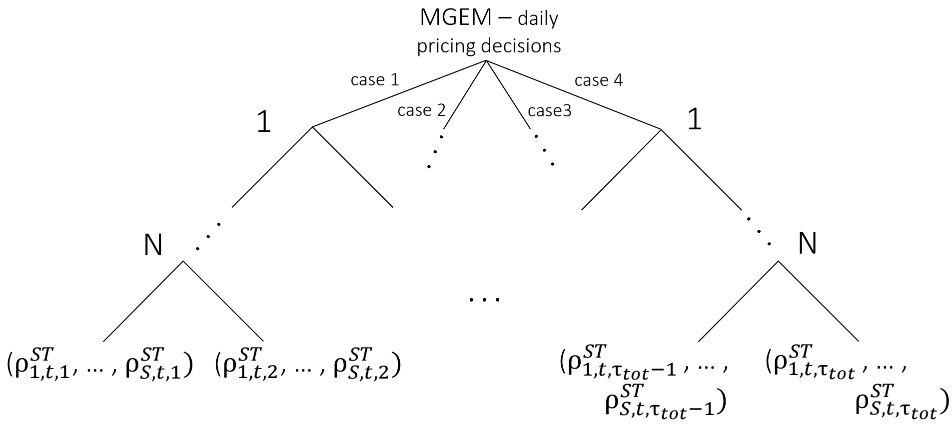


Figure 3.8 – Representation of a short-term extensive tree.

This management is performed for each terminal node of the long-term tree over the $365 \times Y_{tot}$ days of planning. Regarding the co-management of the long and short-term games, this version of the tool is implemented as presented in Fig. 3.9.

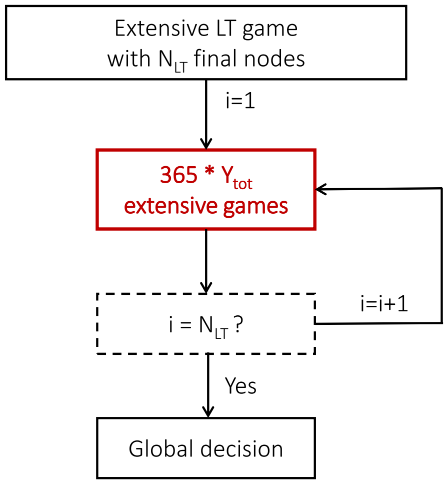


Figure 3.9 – Representation of the long-term extensive game combined with daily extensive games for the tool for small IMGs.

Note that in the current regulatory framework, the considered peak in the companies electricity bill is the one that occurred over the last 12 months. Therefore, in order to align with this rule, the global peak of the IMG is also computed over the last 12 months.

For the first simulated day (day 1, year 1), the short-term cash-flow of each terminal node of the short-term tree is computed according to its respective peak of consumption and a first equilibrium is computed. The global peak corresponding to the node of the equilibrium is therefore the initial global consumption peak, denoted l^{peak}. For all the following days of simulation (over the 20 years), the two steps previously detailed remain unchanged. However, before the computation of short-term cash-flows and equilibrium, a third step has to be added. Indeed, as mentioned above, for the long-term planning of industrial microgrids, the peak of consumption is the higher one over the last 12 months. Therefore, the daily peak computed for each terminal node τ of the ST extensive game of each day, $l^{peak}_{IMG,\tau}$, has to be compared with the current higher global peak l^{peak}:

- If $l_{IMG,\tau}^{peak} < l^{peak}$, the higher peak remains unchanged and the cash-flow of the corresponding node τ is computed with l^{peak}.

- If $l_{IMG,\tau}^{peak} > l^{peak}$, $l_{IMG,\tau}^{peak}$ is used to compute the cash-flow of the node τ.

Note that if the higher peak value has been used for more than 365 consecutive days, a change is imposed. The equilibrium of the short-term tree is then computed according to the defined peak for each node τ (l^{peak} if $l_{IMG,\tau}^{peak} < l^{peak}$ and $l_{IMG,\tau}^{peak}$ otherwise). After computation of the Nash equilibrium, the peak of consumption of the node corresponding to the found equilibrium is the new l^{peak} considered for the next day.

3.1.5 Global solution with long-term decisions

At this stage of the tool, the final decision of long-term investments must be taken. For that purpose, at the end of the $365 \times Y_{tot}$ days, the final cumulated short-term cash-flow $\rho_{s,365\times Y_{tot}}^{ST}$ obtained for each stakeholder s is added to each long-term cash-flow ρ_s^{LT} to constitute a Net Present Value η_s for each stakeholder s (including the DSO). This η_s constitutes the **cost objective function** of the planning problem for each stakeholder (3.4).

$$\eta_s = \rho_s^{LT} + \rho_{s,365\times Y_{tot}}^{ST} \tag{3.4}$$

The long-term cash-flow of each terminal node $\tau_i \in \tau$ of the previously defined long-term tree (Fig. 3.7) is replaced by the corresponding η_s, now denoted η_{s,τ_i} to distinguish the nodes, as illustrated in Fig. 3.10. The equilibrium of this final tree is computed [82] in order to determine the long-term policy to adopt in order to get a global socio-economical welfare inside the IMG while satisfying at best each stakeholder.

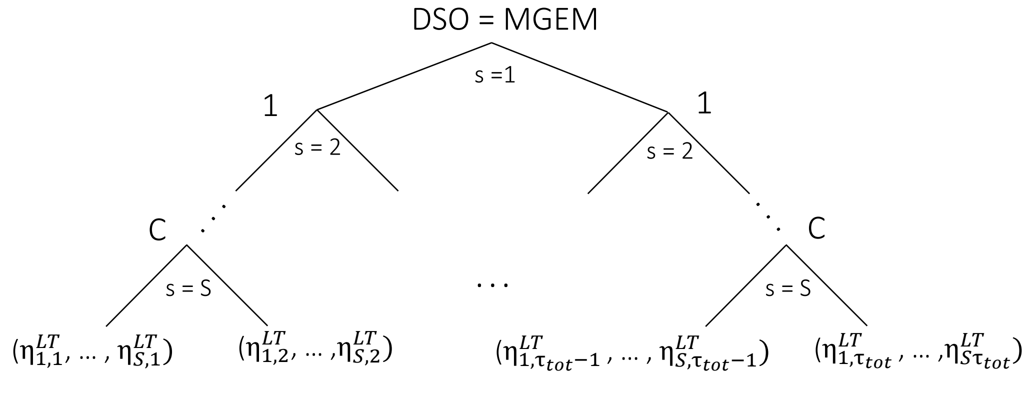


Figure 3.10 – Representation of the final extensive tree.

The final found equilibrium, denoted η_s, will therefore be compared to:

- $\eta_{0,s}$ corresponding to the current situation (*i.e.* without any investments and IMG framework) over the next Y_{tot} years;

- $\eta_{inv,s}$ corresponding to the current situation with only investments (and without IMG framework) over the next Y_{tot} years;

- $\eta_{noLM,s}$ corresponding to the situation described in this chapter (with investments and the new IMG framework) but without LM. This last case will allow to see the benefits (or not) of LM for the concerned stakeholders and is computed in the same way as with LM.

$\eta_{0,s}$ are defined by 3.5, 3.6 and 3.7 for a purchaser, a seller and the DSO, respectively. Note that the $\eta_{inv,s}$ are computed the same way, taking into account the potential generation of new decentralised RESs with its investment cost (ρ_s^{LT}).

$$\textbf{if } s = purchaser$$

$$\eta_{0,s} = \sum_{Y=1}^{Y=Y_{tot}} \Bigg(\sum_{d=1}^{d=365} \sum_{h=1}^{h=24} \big(-\lambda_{s,h} \times (\pi_{out,p,h}, +\pi_{out,p,h}^{fee,d} + \pi_{out,p,h}^{fee,t} + \pi_{out,p,h}^{taxes} + \pi_{out,p,h}^{new})\big) - l_s^{peak} \times (\pi_{out,p}^{peak,d} + \pi_{out,p}^{peak,t}) - \pi_{out,p}^{met} \Bigg) \times \frac{1}{(1+r)^Y} \tag{3.5}$$

$$\textbf{if } s = seller$$

$$\eta_{0,s} = \sum_{Y=1}^{Y=Y_{tot}} \Bigg(\sum_{d=1}^{d=365} \sum_{h=1}^{h=24} \big(g_{s,h} \times (\pi_{out,s,h} - \pi_{out,s,h}^{fee,d})\big) - \pi_{out,s}^{met} \Bigg) \times \frac{1}{(1+r)^Y} \tag{3.6}$$

$$\textbf{if } s = DSO$$

$$\eta_{0,s} = \sum_{Y=1}^{Y=Y_{tot}} \Bigg(\sum_{d=1}^{d=365} \sum_{h=1}^{h=24} \big(\pi_{out,s,h}^{fee,d} \times \sum_{s=1}^{s=S} g_{s,h} + \pi_{out,p,h}^{fee,d} \times \sum_{s=1}^{s=S} \lambda_{s,h}\big) + \pi_{out,p}^{peak,d} \sum_{s=1}^{s=S} l_{out,s}^{peak} + N_{purchasers} \times \pi_{out,p}^{met} + N_{sellers} \times \pi_{out,s}^{met} \Bigg) \times \frac{1}{(1+r)^Y} \tag{3.7}$$

3.2 Application of the planning tool on a small IMG: results analysis

In this study case, the IMG is composed of 3 companies ($C = 3$): 2 consumers (1 and 2) and 1 prosumer (3). Therefore, the planning problem takes into account 4 stakeholders: the DSO as MGEM and the three companies. This IMG is connected to the 10.5 kV DN and illustrated in Fig. 3.11. For each company, three years of load data are available and analysed. Companies 1 and 3 are considered as companies from Class 2 ($C_2 = 2$) while the company 2 belongs to Class 1 ($C_1 = 1$).

For the STEM, only 1 and 3 have consumption profiles which allow doing LM ($C_{LM} = 2$). Regarding the LT decisions, the consumers 1 and 2 can either invest in a PV installation (PV) or do nothing (No). The prosumer (3) can choose to invest in an ESS or to do nothing (No). The uncertain evolution of consumption and prices profiles are taken into account through the nine scenarios previously described.

The available decisions for the DSO/MGEM are linked to the pricing of the IMG framework. Therefore, two LT decisions can be considered: medium prices (MP) and low prices (LP). For

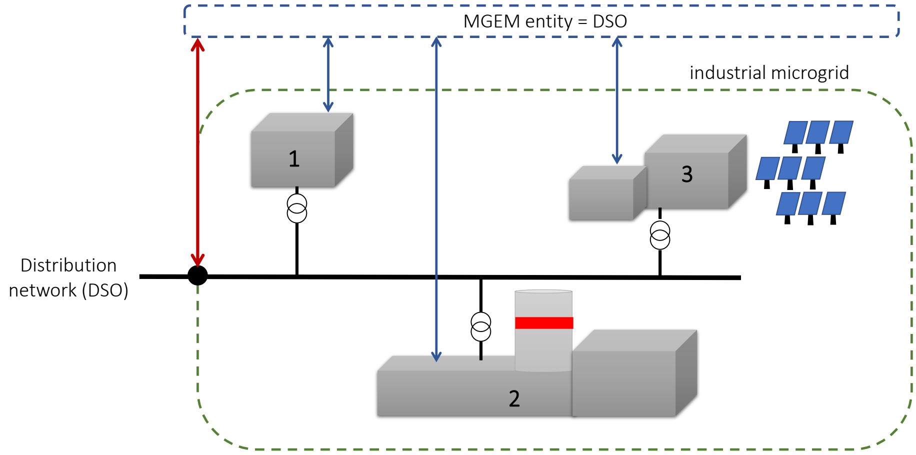


Figure 3.11 – Representation of the IMG studied for the application of the tool.

the second one, pricing is arranged in order to be more interesting for the prosumers/consumers ($i.e.$ a lower IMG fee than for the medium prices case).

The planning tool is applied to this IMG and the results analysis is divided into two main parts. The first one focuses on the LT results with the analysis of the net present values (η_s), the time of return on investments, the occurrence of LM and the internal and external exchanges. The second one shows the benefits of LM and the new method of computation of each consumer/prosumer peak of consumption for a chosen day. Note that, for this study, only DLM is applied.

Regarding the pricing inside the IMG, the new terms have already been defined but some values still have to be fixed, according to the simulation realised. For the simulations presented below, the following pricing has been applied:

- The purchasing and selling commodity prices are equal ($\Pi_{in,p} = \Pi_{in,s}$);
- The purchasing fee for the MGEM ($\Pi^{fee}_{in,p}$) is arbitrarily defined in order to respect the constraint $\Pi^{fee}_{in,p} + \Pi_{in,p} < \Pi^{fee,d}_{out,p} + \Pi_{out,p} + \Pi^{taxes}_{out,p} + \Pi^{new}_{out,p}$ when the inside commodity price has the same trend than the outside commodity price;
- The peak of consumption fee for the MGEM ($\pi^{peak}_{in,p}$) is currently taken as 20% of $\pi^{peak,d}_{out,p}$;
- The selling fee for the MGEM ($\Pi^{fee}_{in,s}$) is also arbitrarly defined in order to respect the constaint: $\Pi_{in,s} - \Pi^{fee}_{in,s} > \Pi_{out,s} - \Pi^{dist}_{out,s}$ when the inside commodity price has the same trend than the outside commodity price;
- The metering cost (π^{met}_{in}) is currently taken equal to $\pi^{met}_{out,p}$.

3.2.1 Analysis of long-term results

After having simulated the nine scenarios ($\Psi_1, ..., \Psi_9$), they all provide the same global equilibrium:

- **MGEM:** Make medium prices;
- **Company 1:** Invest in a PV installation. The power of this installation is around 180 kW if its consumption remains constant over the planning horizon, 250 kW if its consumption increases and 160 kW if its consumption decreases;
- **Company 2:** Invest in a PV installation. The power of this installation is capped at 400 kW whatever the scenario;
- **Company 3:** Do nothing.

Those results mean that a PV installation, with its current price, seems interesting, for all kinds of company. However, an ESS seems too expensive with the considered prices. The new IMG, after investments suggested by the equilibrium, is presented in Fig. 3.12.

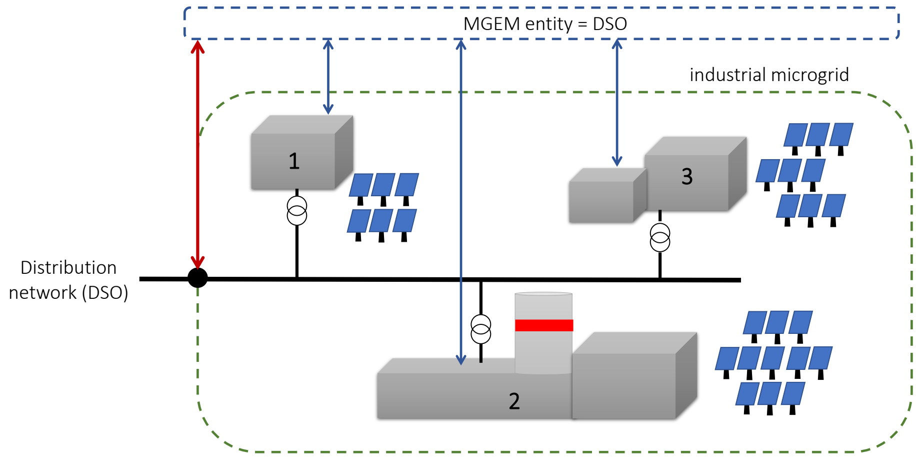


Figure 3.12 – Representation of the IMG with the new investments from the found equilibrium.

The different final NPVs (η_s, $\eta_{0,s}$, $\eta_{inv,s}$ and $\eta_{noLM,s}$) are observed for the 9 simulated scenarios. For that purpose, the computed NPVs with investments are compared to the current one, leading to 3 cases that must be analysed for each stakeholder s:

1) Comparison between the current situation and the situation with investments only:

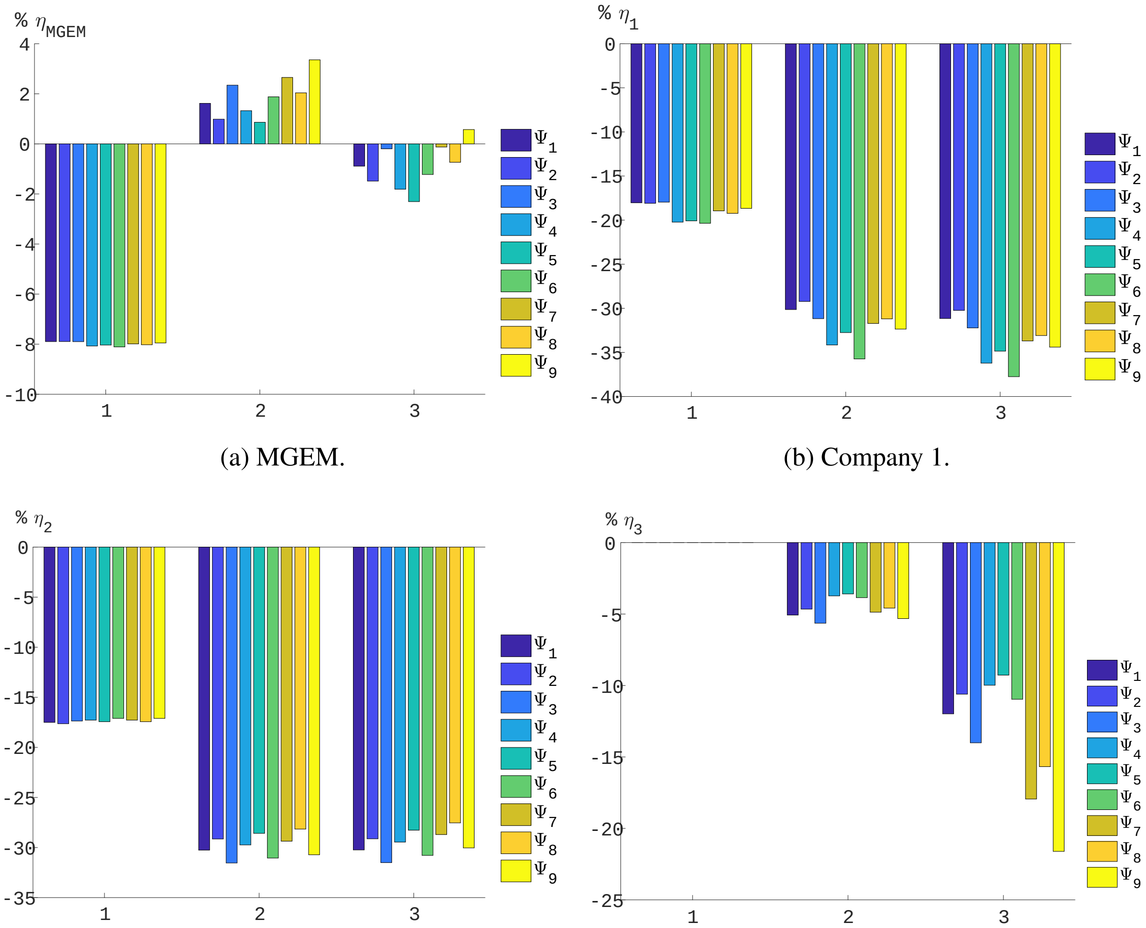
$$\%\eta_s = \frac{(\eta_{inv,s} - \eta_{0,s})}{\eta_{0,s}} \tag{3.8}$$

2) Comparison between the current situation and the situation with investments and the new IMG framework:

$$\%\eta_s = \frac{(\eta_{noLM,s} - \eta_{0,s})}{\eta_{0,s}} \tag{3.9}$$

3) Comparison between the current situation and the situation with investments and the new IMG framework, including DLM:

$$\%\eta_s = \frac{(\eta_s - \eta_{0,s})}{\eta_{0,s}} \tag{3.10}$$



(a) MGEM. (b) Company 1.

(c) Company 2. (d) Company 3.

Figure 3.13 – Percentages of gain/loss for all stakeholders.

The simulations results are presented in Fig. 3.13. For the DSO (=MGEM) (Fig. 3.13a), in the first case, his role of MGEM is not applied and therefore, as there are some investments in RESs, the exchanges with the distribution network are decreased and the DSO looses money (about 8%). These losses are erased thanks to the IMG and his role of MGEM (case 2), even leading to small gains. The effect of LM (case 3) slightly decreases the benefits of the IMG for the DSO given that LM allows an increase of the self-consumption rate inside the IMG (leading to less exchanges, and therefore, less fees for the MGEM).

For companies 1 and 2 (Fig. 3.13b and 3.13c), the solution of investing in a PV installation seems really appropriate because their savings are quite important (between 15 and 20%), even without IMG. Thanks to the IMG framework (cases 2 and 3), an additional saving of 10 to 15% is realised. Regarding the benefit of LM, only the first company is able to perform some. The saving percentage is slightly increased in the third case. For the second company, savings are almost the same for cases 2 and 3. For the company 3, the first case is not valid as no investments are realised. Case 3 allows to see the huge benefit of LM (see Fig. 3.13d). Indeed, for all scenarios, the percentages of saving are almost doubled thanks to DLM (case 3) compared to the case 2.

Analysis of the time of return on investment

In this section, the return rates (RR) of the PV investments of companies 1 and 2 are analysed. For that purpose, the times of return on investment without and with IMG, including DLM, denoted $ROI_{inv,c}$ and $ROI_{\mu g,c}$ respectively, are compared and the RR_c are computed by (3.11) for each company c.

$$RR_c = \frac{ROI_{\mu g,c} - ROI_{inv,c}}{ROI_{inv,c}} \tag{3.11}$$

Tab. 3.1 gathers the registered values for $ROI_{\mu g,c}$ and $ROI_{\mu g,c}$ for the nine scenarios simulated and for $c = 1$ and $c = 2$. The RR_c value is also computed for each of them.

	Company 1			Company 2		
	$ROI_{inv,1}$ [years]	$ROI_{\mu g,1}$ [years]	RR_1 [%]	$ROI_{inv,2}$ [years]	$ROI_{\mu g,2}$ [years]	RR_2 [%]
Ψ_1	8.7	6.2	-28.7	9.7	7.2	-25.8
Ψ_2	8.3	5.9	-28.9	9.3	6.9	-25.8
Ψ_3	9.2	6.4	-30.4	10.2	7.5	-26.5
Ψ_4	8.9	6.3	-29.2	9.7	7.1	-26.8
Ψ_5	8.4	6.1	-27.4	9.2	6.9	-25.0
Ψ_6	9.3	6.6	-29.0	10.2	7.4	-27.5
Ψ_7	8.7	6.1	-29.9	9.7	7.2	-25.8
Ψ_8	8.2	5.8	-29.3	9.2	6.8	-26.1
Ψ_9	9.2	6.3	-31.5	10.2	7.3	-28.4

Table 3.1 – Analysis of the times of return on investment

Note that if the LM is not performed by 1 and 2, RR_1 is increased of about 3% and RR_2 is not significantly changed.

Load management occurrence over the 20 years of planning

In this section, the occurrence of DLM over the $5\times52\times20 = 5200$ working days of the planning horizon is analysed. Tab. 3.2 gathers those results for each scenario for companies 1 and 3. We can observe that DLM is performed most of the time for both companies. This result does not seem realistic being balanced with the low financial benefits arising from its application. However, DLM is performed between 6am and 6pm, without any constraints or limitation. The DLM process could therefore be adapted to the company consumption profile because sometimes, the peak of consumption occurs outside the hours of the defined period. Moreover, as already mentioned in the previous section, DLM is sometimes performed to fit consumption to generation, even if the generation is low. In this last case, the peak of consumption is not necessary decreased. It should therefore be interesting to apply DLM in order to realise peak shaving while fitting consumption to generation or, at least, to add the constraint to also decrease the peak of consumption. We can also conclude that the small variations of the DLM occurrence are only linked to the LT evolution of the load profiles.

	Company 1 DLM % of occurrence	Company 3 DLM % of occurrence
Ψ_1	74.56	76.25
Ψ_2	74.56	76.25
Ψ_3	74.56	76.25
Ψ_4	75.88	75.73
Ψ_5	75.88	75.73
Ψ_6	75.88	75.73
Ψ_7	75.63	77.12
Ψ_8	75.63	77.12
Ψ_9	75.63	77.12

Table 3.2 – Analysis of the occurrence of LM over the 20 years of planning

In this version of the tool, the benefit of DLM is limited and quite difficult to observe. There is no significant variation regarding the moments of the year, and even if DLM in often applied for both companies, the financial benefit is only significant for the company 3.

3.2.2 Electricity internal and external exchanges analysis

In this section, the operation of the IMG as a whole is analysed. This analysis rests on the observation of the exchanges with the DN (IMG-to-DN exchanges) on the one hand and inside the IMG (peer-to-IMG exchanges) on the other hand. The parameters used are inspired from new metrics coming from [92]. Those metrics have been adapted in order to take into account the long-term nature of this analysis. Therefore, they are computed over the Y_{tot} years of planning. This section is divided into four parts: the first one is dedicated to the peer-to-IMG exchanges, the second one focuses on the IMG-to-DN exchanges, the third one presents the self-consumption rates of companies 1, 2 and 3 for all scenarios and the last one is a brief load flow analysis.

Peer-to-microgrid exchanges

Tab. 3.3 summarises the installations and exchanges inside the IMG for the found equilibrium of each scenario. The analysis parameters are defined as follows:

- TIC = Total Installed Capacity;
- REP = Renewable Energy Penetration (ratio between the total kWh renewable energy produced and the total kWh electricity demand);
- IEP = Internal Exchanges Probability (ratio between the total hours of internal exchanges and the total hours of operation $8760 \times Y_{tot}$);
- IEE = Internal Energy Exchanges;

	TIC [kW]	REP [pu]	IEP [pu]	IEE [GWh]
Ψ_1	830.82	0.3299	0.2201	1.6312
Ψ_2	830.82	0.3299	0.2201	1.6312
Ψ_3	830.82	0.3299	0.2201	1.6312
Ψ_4	897.42	0.3187	0.2241	1.9825
Ψ_5	897.42	0.3187	0.2241	1.9825
Ψ_6	897.42	0.3187	0.2241	1.9825
Ψ_7	811.25	0.3545	0.2258	1.4141
Ψ_8	811.25	0.3545	0.2258	1.4141
Ψ_9	811.25	0.3545	0.2258	1.4141

Table 3.3 – Analysis of the parameters for peer-to-microgrid exchanges

First of all, we can see that, even if the power of the new installation is adapted to the evolution of the consumption profiles over the 20 years of planning (variations of the TIC), the REP is more or less stable but still a little lower when the consumption increases (Ψ_4, Ψ_5 and Ψ_6) and a little higher when the consumption decreases (Ψ_7, Ψ_8 and Ψ_9) compared to the situation during which the consumption remains constant (Ψ_1, Ψ_2 and Ψ_3). That means that the increase of the installed power could be more significant to counter the consumption rise and to obtain an higher penetration of RESs. The IEP is more of less constant for all scenarios. The values of IEE are directly related to the previous observations: given that for scenarios Ψ_4, Ψ_5 and Ψ_6 both the load and the generation are high, the IEE is the highest. At the opposite, it is the lowest for the scenarios Ψ_7, Ψ_8 and Ψ_9.

Exchanges with the distribution network

Tab. 3.4 allows the analysis of the exchanges between the IMG and the DN. The different parameters of analysis are:

- PP = Purchase Probability (ratio between the sum of hours when the IMG purchases energy from the DN and the total grid-connected hours);
- TEP = Total Energy Purchased;
- SP = Sale Probability (ratio between the sum of hours when the IMG sales energy to the DN and the total grid-connected hours);
- TES = Total Energy Sold;

Note that, as the considered IMG is always connected to the DN, the total grid-connected hours are $8760 \times Y_{tot}$.

The purchasing parameters (PP and TEP) follow correctly the trend of the global consumption: compared to the scenarios Ψ_1, Ψ_2 and Ψ_3, they increase when the global consumption is higher as the REP is lower and there is more energy to purchase to cover all the consumption (scenarios Ψ_4, Ψ_5 and Ψ_6) and therefore, they decrease when the consumption is lower (scenarios

	PP [pu]	TEP [GWh]	SP [pu]	TES [GWh]
Ψ_1	0.8751	42.703	0.1249	3.5560
Ψ_2	0.8751	42.703	0.1249	3.5560
Ψ_3	0.8751	42.703	0.1249	3.5560
Ψ_4	0.8820	48.273	0.1180	3.6021
Ψ_5	0.8820	48.273	0.1180	3.6021
Ψ_6	0.8820	48.273	0.1180	3.6021
Ψ_7	0.8545	38.369	0.1455	4.2003
Ψ_8	0.8545	38.369	0.1455	4.2003
Ψ_9	0.8545	38.369	0.1455	4.2003

Table 3.4 – Analysis of the parameters for the exchanges with the DN

Ψ_7, Ψ_8 and Ψ_9). The trend is reversed for the selling parameters (SP and TEP) which means that the self-consumption rate is probably higher in scenarios Ψ_4, Ψ_5 and Ψ_6 and lower in scenarios Ψ_7, Ψ_8 and Ψ_9 than for a constant load profile evolution.

Self-consumption rates

Given the previous observations, it seems interesting to observe the self-consumption rate (SCR_c) of each company c to confirm them as well as the global self-consumption of the IMG SCR_{IMG}. It seems also interesting to observe the influence of DLM on these rates. Tab. 3.5 gathers all the SCR_c values. The self-consumption rate is here defined as the ratio between the energy directly consumed by a company (the IMG) and the total generation of this company (of the IMG).

	Without DLM				With DLM			
	SCR_1 [%]	SCR_2 [%]	SCR_3 [%]	SCR_{IMG} [%]	SCR_1 [%]	SCR_2 [%]	SCR_3 [%]	SCR_{IMG} [%]
Ψ_1	90.56	61.15	79.17	73.09	89.57	62.15	74.03	71.54
Ψ_2	90.56	61.15	79.17	73.09	89.57	62.15	74.03	71.54
Ψ_3	90.56	61.15	79.17	73.09	89.57	62.15	74.03	71.54
Ψ_4	87.54	60.46	81.37	73.30	86.77	60.46	77.39	72.14
Ψ_5	87.54	60.46	81.37	73.30	86.77	60.46	77.39	72.14
Ψ_6	87.54	60.46	81.37	73.30	86.77	60.46	77.39	72.14
Ψ_7	87.86	60.46	75.14	70.12	86.98	60.46	69.55	68.47
Ψ_8	87.86	60.46	75.14	70.12	86.98	60.46	69.55	68.47
Ψ_9	87.86	60.46	75.14	70.12	86.98	60.46	69.55	68.47

Table 3.5 – Analysis of the self-consumption rates

Globally, the self-consumption trends deduced from the exchanges analysis are verified: for scenarios corresponding to the increase of the consumption profiles (Ψ_4, Ψ_5 and Ψ_6), the decrease of the IEE and of the SP reflects a higher global self-consumption rates. For the scenarios corresponding to the decrease of the consumption profiles (Ψ_7, Ψ_8 and Ψ_9), the self-consumption rate is, at the opposite, lower. Note that the prices evolution does not affect significantly all kinds of exchanges as well as the self-consumption rates.

Load Flow analysis

For each day, a load flow (inspired from [93]) is conducted in order to detect some issues of overvoltage or congestion. However, given that the considered IMG is connected to the 10.5 kV DN, three PV installations are probably not enough to induce notable disturbances and, indeed, no problems have been identified, whatever the considered scenario. If some congestions or over-voltages would appear, the total amount of RESs installed should be limited to the grid capacity constraint.

3.2.3 Zoom on a day for short-term results

For the same IMG as the one considered in the previous section, a "zoom" has been realised for a random day in order to see the benefits of the use of DLM and the new method of computation of the peak of consumption of each consumer/prosumer [87]. This day has been simulated with PV installations for only companies 2 and 3 in order to allow the company 1 to perform DLM_{cons} and the company 3 to perform DLM_{pros}. The daily extensive tree is illustrated in Fig. 3.14 and the daily profiles of the three companies are shown on Fig. 3.15a, 3.15b and 3.15c, respectively. In these figures, the initial profile (L_s) is superimposed to the modified one ($L_{s,LM}$) for 1 and 3, and to their generation (P_s) for 2 and 3.

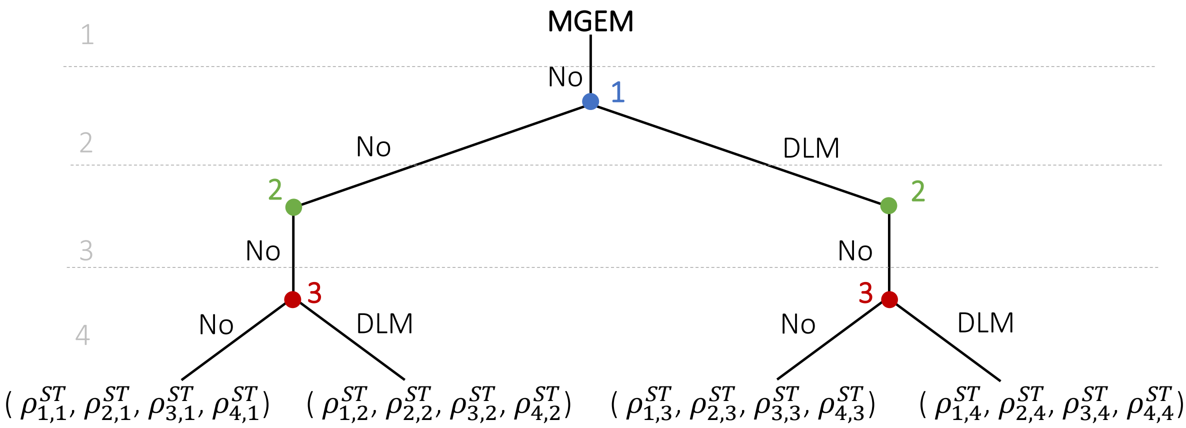
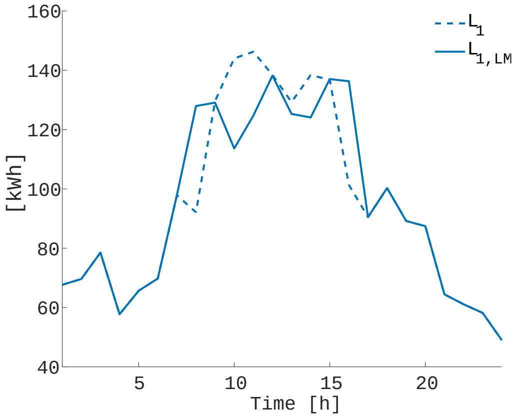
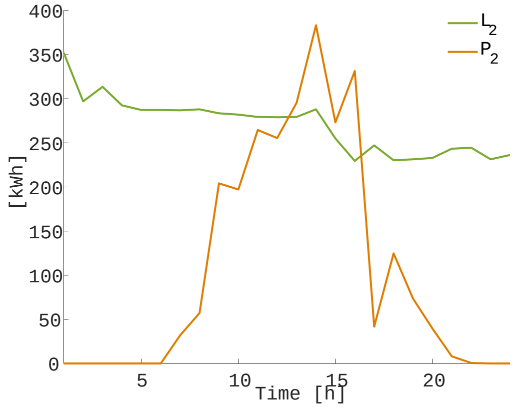


Figure 3.14 – Representation of the extensive game for the considered day.

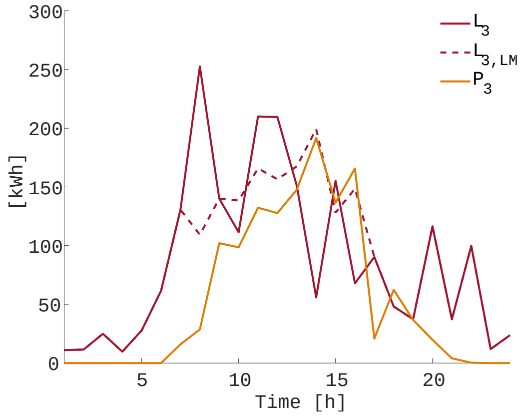
The computed equilibrium corresponds to the fourth node, which means that for this day, both 1 and 3 have to realise DLM. Fig. 3.16 shows the exchanges inside the IMG and with the DN for this equilibrium. The full lines are for node 4 and the dashed lines are without any DLM (corresponding to node 1). With DLM, the company 3 increases its self-consumption rate (from 79.71% to 97.77%) and sells its small excess of generation inside the IMG. Globally, the sales to the grid are erased thanks to DLM. Indeed, the fact that company 3 has less electricity to sell inside the IMG to company 1, during hours 14 and 16, allows company 2 to sell all its excess of electricity inside the IMG to company 1.



(a) c=1.



(b) c=2.

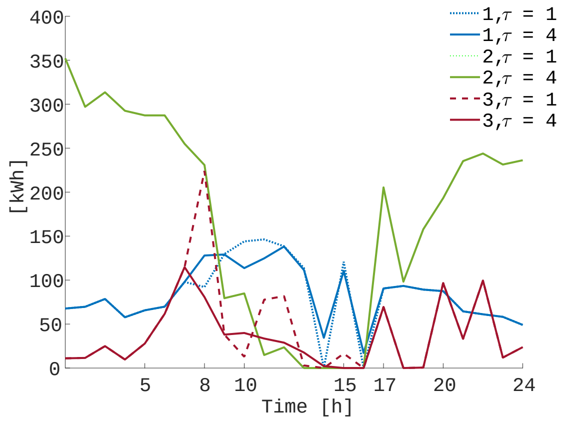


(c) c=3.

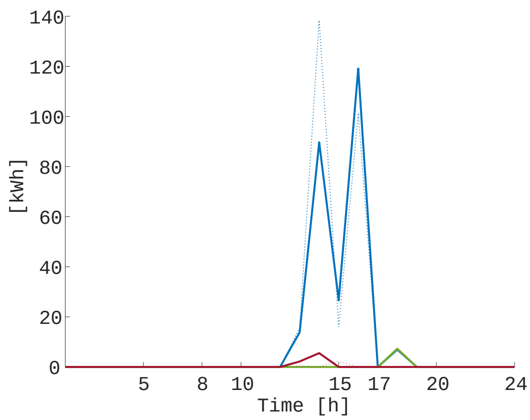
Figure 3.15 – Profiles of consumption for the considered day.

The peak of consumption, from the point of view of the DN, is decreased from 547 to 467.5 kW thanks to DLM. For consumers and prosumers, the peak of consumption with DLM, computed as described above, is significantly reduced (see Table 3.6). Tab. 3.6 also shows the economical saving for each company c, which is computed by the ratio between the cash-flow ($\rho_{c,d,4}$) of the solution with DLM ($\tau = 4$) minus the one without DLM ($\rho_{c,d,1}$), and $\rho_{c,d,1}$. For companies 1 and 2, this value is negative which means that they spend less money. For company 3, this value is an earning, which means that its incomes (positive cash-flows) are increased.

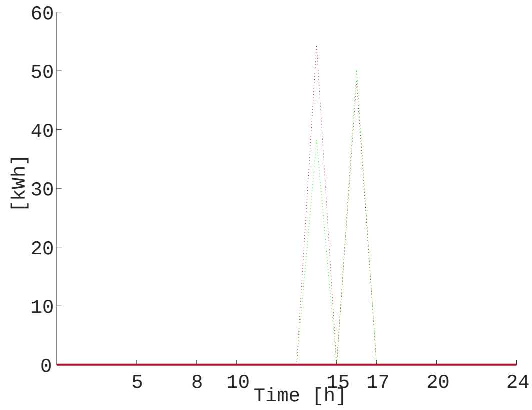
However, this important load peak reduction leads to small losses for the DSO/MGEM. Regarding the other nodes, only the third one allows the manager to do some benefits, but all the other stakeholders are losing money. The node 2 is almost equivalent to the node 4, but with less important benefits for the 3 companies because, even if the peak of consumption is the same than for node 4, there are more exchanges with the DN. Therefore, this solution should not be chosen to comply with the initial goals of the IMG concept.



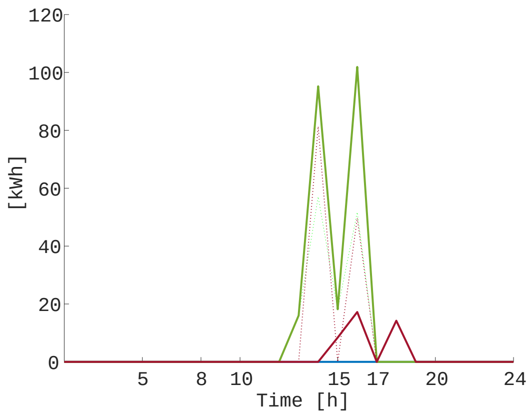
(a) Purchage to grid.



(b) Purchase to IMG.



(c) Sale to grid.



(d) Sale to IMG.

Figure 3.16 – Peer-to-microgrid and external exchanges.

	l_c^{peak} $[kW]$	$l_{c,LM}^{peak}$ $[kW]$	Savings (-) & Earnings (+) [%]
c=1	92.1	78.7	-1.13
c=2	230.8	197.3	-12.92
c=3	224.1	191.5	+ 35.44

Table 3.6 – Peak value and savings analysis

To observe the microgrid as a whole for nodes 1 and 4, some of the metrics previously presented and inspired from [92] are this time computed over the 24 hours of simulation. They are presented in Tab. 3.7 and described as follows:

- IEP = Internal Exchanges Probability (ratio between the total hours of internal exchanges and the 24 hours of operation);
- IEE = Internal Energy Exchanges over 24 hours;
- PP = Purchase Probability (ratio between the sum of hours when the microgrid purchase energy from the DN and the 24 grid-connected hours);
- TEP = Total Energy Purchased over 24 hours;

- SP = Sale Probability (ratio between the sum of hours when the microgrid sale energy to the DN and the 24 grid-connected hours);
- TES = Total Energy Sold over 24 hours;

Those results globally show that the amount of electricity exchanges inside the IMG and with the DN are decreased when DLM is applied. Inside the IMG, the number of hours of exchanges remains constant but the quantity of electricity exchanged is slightly decreased. With the DN, the amount of electricity purchased over the day is decreased (even if the IMG purchases electricity during more hours) and the amount of electricity sold is equal to zero. These changes are mainly linked to the self-consumption rate increase of the company 3.

	IEP [pu]	IEE [kWh]	PP [pu]	TEP [MWh]	SP [pu]	TES [kWh]
τ=1	0.2083	288.1394	0.9167	7.1545	0.0833	190.9418
τ=4	0.2083	271.1517	1	6.9635	0	0

Table 3.7 – Daily internal and external exchanges analysis with DLM.

3.3 Limitations and weaknesses of the tool

The main limitation of the tool comes from the complexity of an extensive game. Indeed, the number of terminal nodes (which are the configurations to be simulated in the tool) drastically increases with the number of players and the number of actions. Indeed, the number of terminal nodes LT is computed by $N_{LT} = \prod_{s=1}^{S} m_s$, where m_s are all possible actions of the stakeholder s. In the simulated IMG, all the players s ($S = 4$) have the same number of possible actions ($m_s = 2$), leading to an extensive game of $2^4 = 16$ terminal nodes. If we add some other LT decisions, as for classical example the possibility of choosing WT, and if the size of the IMG grows up to 20 players, the LT extensive game will have $N_{LT} = 3^{20}$ terminal nodes, which corresponds to more than $N_{LT} = 3 \times 10^9$. Obviously, it seems quite difficult to manage the short-term simulations for so many configurations.

Moreover, currently, with DLM, the CPU time requested for simulating one day is $19s$. Given than 20 years of 365 days must be simulated for the N_{LT} configurations, that leads to a global CPU time of $365 \times 20 \times 3 \times 10^9 > 1800 years$. Of course, some parts of the simulation could be realised in parallel but, clearly, the methodology should be rethought to manage in a better way larger IMG including more decisions.

Regarding the main weaknesses of the tool, the first one is the data long-term forecasting. In the first version of the tool, a sampling is realised for each day, and its convergence is not checked. Indeed, the assumption has been made that 365×20 samples were enough to ensure an accurate result. Therefore, from one simulation to an another, some variations could be observed. The convergence of the sampling and the stability of the results should therefore be checked in an updated version of the tool.

The second weakness comes from the LM. Given the observed results, its application should be revised to be more significant for the companies regarding its benefits. Moreover, in relation with the previous comment, its application should be performed based on more reliable data profiles.

3.4 Conclusion

This chapter was devoted to a first version of a planning tool for IMGs. The current version of the tool concerns small IMGs, with only 4 players and 2 LT decisions. The set up principle was to run the 20 years of simulations, including the STEM, to obtain a NPV for each stakeholder and to take the LT decisions of investments (including PV and ESS).

The performance of the different steps of the tool have been demonstrated through a test case. Regading the LT decisions making process, the simulations show that PV installations are financially interesting while the ESS are still to expensive to be profitable. The use of the new IMG framework for the energy management inside the IMG allows all the companies to make additional benefits compared to the situation without IMG (with only investments). The latter also allows the DSO to reduce its losses linked to the IMG development (and the decrease of the exchanges with the DN) thanks to its role of MGEM and the fees established inside the IMG.

Regarding the LM, its benefits have been observed for only one company. That means that its definition and use could still be improved and adapted according to the load profiles and the particular activities/processes of the companies.

Even if this tool globally works properly for small IMGs, some weaknesses regarding its extension to more companies with more decisions have been shown. Indeed, as the LT game size grows exponentially and the ST games are solved for each simulated day, the computation time of this version of the tool would become too huge to be realistic. Therefore, the remaining part of this work will focus on some ways to reduce the complexity and the computation time of the tool in order to extend it to more companies, decisions and considerations.

3.5 Chapter publications

This chapter had led to the following publications:

- C. Stevanoni, Z. De Grève, F. Vallée, Member, IEEE, and Olivier Deblecker, "Long-Term Planning of Connected Industrial Microgrids: A Game Theoretical Approach Including Daily Peer-to-Microgrid Exchanges", *IEEE Trans. On Smart Grid*, Vol. 10, No. 2, pp. 2245-256, March 2019.
- C. Stevanoni, F. Vallée, Z. De Grève and O. Deblecker,"On the use of game Theory to study the planning and profitability of industrial microgrids connected to the distribution network", *In Proc. 24th International Conference on Electricity Distribution (CIRED 2017)*, Glasgow, Scotland, June 2017.
- C. Stevanoni, F. Vallée, Z. De Grève and O. Deblecker, "Daily Game Theoretical Management of a Connected Industrial Microgrid", *In proc. 2017 IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia)*, Auckland, New-Zealand, Dec. 2017.

Chapter 4

Extension of the tool to larger microgrids with additional decisions while reducing simulation complexity

The general concept of the IMG planning has been demonstrated in chapter 2 and 3. However, some limits and weaknesses have been highlighted. The following of the research has then to focus on these last ones. For that purpose, three main research axes have been explored:

- The one relative to the potential application of other kinds of games to reduce the complexity and the computation time of the tool;
- The one relative to the use of clustering to reduce the number of days to be simulated by the tool over the 20 years of planning;
- The one relative to the use of Monte Carlo sampling to generate typical days while achieving the convergence of the predicted data with the tool.

This chapter presents how these research axes have been dealt with. The first part of the chapter is dedicated to both researches on the game theory and clustering aspects. The second one focuses on an original way to use a Monte Carlo sampling of the data.

4.1 Approaches considered to reduce the complexity and the simulation time of the tool

The first research axis is oriented towards the game theory field. Indeed, there exist lots of games and the idea is to adapt the initially formulated game in another one which could be less time consuming. Both LT and ST games are concerned by this research but their respective problem is not the same. Indeed, the LT game is concerned by a size problem while the ST game is more concerned by the number of executions. Therefore, this section is divided into two parts dedicated to each challenge.

4.1.1 Game Theory approach: different kinds of games to reduce LT game complexity and size

As previously mentioned, the size of the LT game is drastically increasing with both the number of players and the number of decisions. If all players S have the same number of actions m_S, the number of terminal nodes N_{LT} is given by $N_{LT} = \prod_{s=1}^{S} m_s$. Therefore, it is better to increase the number of actions than the number of players. For that purpose, two kinds of new games could be considered: the coalition games and the partial games.

Coalition games

In the coalitions games, the players are gathered by groups (called coalitions) to which are associated actions. Each action is linked to a global gain that must be divided between the members of the coalition. The main point of such games is therefore the repartition of the gain between the coalition members. For that purpose, two main methodologies are presented in [94]:

- The Shapley value: this methodology rests on the division of the gains according to the marginal contribution of the players to the coalition. The Shapley value is based on three axioms: the symmetry (if two players contribute in the same way to the coalition, they perceive the same gain), the dummy player (if a player does not contribute to the coalition, he perceives nothing) and the additivity (if the game is divided, the gains are also divided). Therefore, for a coalition game of S players and $v(\kappa)$ the valued payoff of each coalition $\kappa \subseteq S$, the Shapley Value distributes the payoffs to each player i according to (4.1). In this equation, the last term (between brackets) is the contribution of player i when he is added to the coalition κ, $|\kappa|!$ is the possible arrangements of players inside the coalition κ and $(|S| - |\kappa| - 1)!$ is the same for the remaining players. Those terms are added over the whole possible coalitions κ and divided by all the arrangements of the players N.

$$\phi_i(S, v) = \frac{1}{S!} \sum_{\kappa \subseteq S \backslash i} |\kappa|!(|S| - |\kappa| - 1)![v(\kappa \cup i) - v(\kappa)] \tag{4.1}$$

- The core value allows to define if the players prefer forming a coalition or stay independent. In other words, that allows to check if the gain of each player i inside a coalition κ is higher than without any coalition (independent players) [94].

The main problem of coalition games is that it is necessary to compute once the game with all independent players in order to build the proper coalitions and to see their benefits. In our case, that is not interesting as the idea is to reduce the computation time of the developed tool. Therefore, such a game does not seem appropriate to apply in the tool.

Partial games

The principle of a partial game is to divide the large game into smaller games in order to reduce both the complexity and the simulation time of the game solving [95]. Different approaches can be considered but they all imply an independence between some players (and their decisions). **Unfortunately, this solution seems therefore not appropriate to the planning tool given**

that all players are depending one from each others through the energy exchanges in the IMG operation. Indeed, the cash-flow, and then the preference, of each player is linked to its own load (and potentially generation) profiles but also to the ones of the other players leading to different quantities of electricity to exchange inside the IMG and with the DN and then to different incomes/outcomes. Therefore, such a game is not realistic in the developed planning tool.

4.1.2 Game theory approach to decrease the number of simulated games

The second approach to reduce the computation time of the first version of the tool thanks to game theory focuses on the ST game. This part of the scientific approach is based on the fact that each day, among the 7300 simulated ones, is characterised by similar games, *i.e.* with the same decisions. Therefore the research is moved towards repeated games (stochastic or not).

Repeated Games

A multi-stage game is a succession of stage games (*e.g.* extensive games) played sequentially by the same players. The sequence of outcomes is evaluated by the total payoffs of the played games. Note that each player can observe the outcomes of the previous games before another game is played. This principle allows the players to condition their future actions. By definition, the payoff of the player i playing the t^{th} stage-game is u_i^t and his total payoff is u_i:

$$u_i = u_i^1 + u_i^2\delta + u_i^3\delta^2 + \ldots + u_i^T\delta_{T-1} \tag{4.2}$$

$$= \sum_{t=1}^{T} u_i^t \delta^{t-1} \tag{4.3}$$

where T is the number of stage-games played $t \in [1 \quad \ldots \quad T]$ [96], [97]. The discount factor $\delta \in [0 \quad 1]$ can be defined according to the interest rate r: $\delta = 1/(1+r)$ [96]. According to this definition, the current methodology applied in the tool is close to such repeated games. Now, let us investigate how to reduce the computation time of such games.

In [98], the authors define a repeated game as a special case of a multi-stage game in which the same stage game is being played at every stage (with the same players and the same payoffs). In such finite games, the total payoff is also expressed by (4.3) [98]. Regarding the equilibrium, the same reference shows that *If a finite multistage game consists of stage games that each has a unique Nash Equilibrium, then the multistage game has a unique subgame perfect equilibrium.* This affirmation is demonstrated thanks to the backward induction principle, *i.e* by solving the game starting with the last stage. Indeed, in this last stage, the players must play the unique NE. In the game before, they did not know the condition of the future (last) game and therefore, they also play the unique NE and so on with the previous stages.

For infinite repeated games, the total payoff is also computed by (4.3) replacing the number of stages T by the infinity. Therefore, given the infinite number of information sets, some solving strategies have to be considered to compute the global payoffs. Two of them are often presented in the literature [82], [99], [100], [101]: the *grim trigger* strategy and the *tit-for-tat* strategy. :

- Grim trigger strategy: the players cooperate until one of them defects. Then, the second player defects and they both continue to defect forever;
- Tit-for-tat: the players cooperate until one of them defects. Both players defect the next round and then go back to cooperation.

Those strategies can be completed by some punishes deviations (see [82]).

Those strategies allow to express the succession of payoffs as a stream in function of δ. The equilibrium is therefore defined in function of the δ value allowing the player to reach the value of the global NE payoff of the repeated game while playing the game only once (and then reducing the computation time of the infinitly repeated game). This definition implies that, at each stage, the same game with the same preferences and payoffs is played. Note that the value of the discount factor can be also chosen to represent the patience of the player: if its value is close to zero, the player cares less about the distant future (impatient player); at the opposite, if δ is close to one, the player is patient [82].

The major problem with this kind of games is that, at each stage, exactly the same game is played. In the developed tool, each day can be seen as a stage of a repeated game. However, even if the same structure of game (same available actions with the same players) is played every day, the payoffs and the preferences attached to each terminal node of the extensive game (stage game) change according to the generation, the load and the prices profiles of the considered day. Therefore, such a methodology that define the global payoff of deterministic repeated games seems not appropriate.

Another way to solve the infinitly repeated games is to use the **Folk Theorem** [102]. This kind of solving methodology is interesting in n-players games because, based on the minmax payoff value defined in [101], [103], it allows to transform the games of n games of two players. However, this still implies that the same game with the same payoffs is (infinitely) played at each stage and the solution is characterised by a region of average values and is thus not exact, which is not really appropiate for the developed tool. Some papers are related to the *non equivalent utilities* [104] and [105], but they are related to games with payoffs equal to zero or one and with different discount factors for each state game or between players, which is also non-applicable to the tool.

Stochastic repeated Games

Stochastic repeated games could therefore be the solution because in such games, the game played at each stage is different. The agents select a game from a set of stage-games and the game played at each iteration depends on the previous game and the actions chosen by the other agents in the latter [101]. The payoffs depend on the action profile played at each stage. The actions chosen at stage t are used to select the game that will be played in the next stage [106]. The transition between the different kinds of stage games is performed randomly, according to the different solving process.

A Markov chain game is a repeated game in which the succession of the different stage-games is defined by a Markov chain. A Markov strategy is a strategy in which a player action profile a_t

is only dependent of the state of the system θ_t in period t and not of the whole history h_t until period t (with $h_t = ((a_1, \theta_2), ..., (a_{t-1}, \theta_t)))$ [107]. The goal of reference [107] is *to show that the payoff-relevant states and the concept of equilibrium in Markov strategies can be defined naturally and consistently in a large class of dynamic games*. The paper focuses in games with observable actions, *i.e.* all the players know the history h_t (as defined above) before choosing their period t actions. Such games could be interesting if the construction of the transition matrix does not imply to simulate an important number of days to evaluate the data (and so the equilibrium) behaviour.

In the same idea, repeated games in literature also appear with the notion of *learning games* [108], *learning equilibrium* [109] - [115] or *learning payoffs* [116], [117] . In such games, the actors also have a set of several games and do not know their initial one or the initial one of the other players. To learn about games, many computations of them need to be realised in pre-processing, which will not decrease the computation time of the tool.

The major challenge linked to the the planning tool is that the payoffs and preferences of a daily game are significantly depending on the load profiles of all companies and of the global RES generation inside the IMG. Therefore, even is the structure of the game is similar for each day, the preferences and the payoffs are different for each one. In the literature relative to game theory, this kind of problem does not seem to have already been considered. Therefore, the study of the equilibrium should not stake on game theory considerations but should also focus on an analysis of data. The found games (as well as the initial formulation) should be applied for categorised days in order to converge towards an equilibrium and so a payoff/preference that will be representative for one type of day (according the load and generation profiles). According to this observation, **the obvious continuation of the research should focus on the data analysis and the possibility of clustering them to obtain groups of days to be simulated allowing a decrease of the simulation time for the ST games.**

4.1.3 Clustering approach to reduce the number of simulated days

The clustering objective is to gather similar objects inside a group called **cluster**. The objects from one cluster to another one must then be dissimilar. In the current literature [118], clustering has be used for:

- Underlying structure of data (*e.g.* to detect outliers or to generate hypothesis);
- Naturally classifying data (*e.g* to identify similar behaviour);
- Compressing data (*e.g* to generate a limited number of representative data or to compute average behaviours inside a cluster).

The latter application seems interesting for improving the tool developed in this thesis as the main idea is to generate typical days to be simulated.

Practically, the clustering methodology is defined by two choices: the method of computation of the distance between objects (to gather them in K clusters) and the way to generate the centroid of the cluster, *i.e*, the most representative object (existing or built) of the cluster. Fig 4.1 illustrates the clustering application on a set of data into $K = 3$ clusters, with a centroid q_i defined for each one (the crosses inside each cluster).

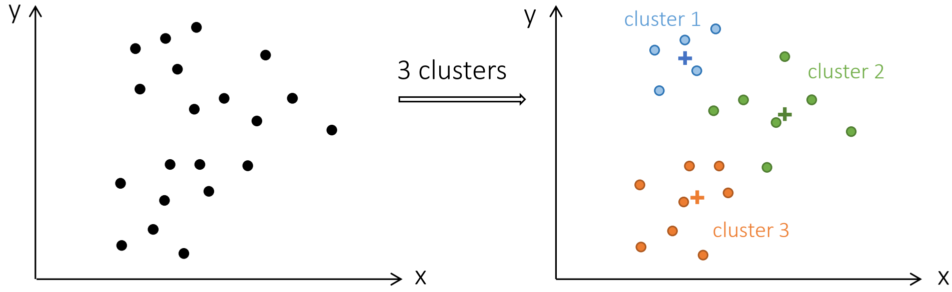


Figure 4.1 – Illustration of clustering.

In our context, the data used are time series (daily load, generation and price profiles). To compute the distance for such series, different methodologies can be considered. These methodologies are briefly defined below:

- Euclidian distance (K-means): The methodology is the most commonly used in clustering. It simply rests on the minimisation of the sum of the squared error between the objtects x_j of each cluster Q_i and its empirical mean μ_i [118]:

$$min \sum_{i=1}^{K} \sum_{x_j \in Q_i} \parallel x_j - \mu_i \parallel^2 \tag{4.4}$$

  The disadvantage of this methodology is that the optimisation can be trapped in a local minimum depending on the initially selected cluster. The methodology is going iteratively from an initial partition of the clusters to the partition with the closest distance between the mean and the objects. The number of clusters K desired must be specified.

- Dynamic Time Warping (DTW): This methodology is based on a dynamic algorithm that finds the optimum warping path between two time series by computing a local cost matrix (for each pair of compared distance) and minimise the alignement (*i.e.* the associated cost) between the series. The detailed mathematical formulation is presented in [120]. The main information to retain is that, as it works locally, a window constraint must be specified (usually about 10% of the serie's length) and a lower bound must be fixed (to decrease the computational time). Another way to decrease the complexity of this methodology is to use soft-DTW, a smoothed version of DTW allowing to use a gradient function, easier to compute;

- Global Alignement Kernel (GAK): This methodology is similar to the DTW one except that a local kernel similarity function considers all possible series alignements. Of course, a contraint must be fixed to reduce the complexity (higher than for DTW) called triangular constraint, also defined in [120].

- Shape-Based Distance (SBD): This methodology is faster than DTW and rests on the " cross-correlation with normalisation coefficients sequence" between series [120]. A cross correlation methodology is exposed in [121].

In the same context, different methodologies of centroid generation can be applied:

- Mean: the most commonly used, with K-means, is, as explained above, the mean value of the cluster Q_i: μ_i.
- Partition Around Medoid (PAM): The particularity of this methodology is that the final centroid is belonging to the initial data (in this case, the centroid can be called medoid). Indeed, for the number of clusters desired K, K initial centroids are arbitrarily chosen and the distances between the elements of the series and those centroids are computed. The closest series-centroids combinations are selected to form a cluster then the distance between all objects of each built cluster is computed. For each serie, the sum of the distances is computed and the one with the lowest sum becomes the new centroid, and so on until convergence [120].
- DTW barycenter average (DBA): this methodology is directly linked to the DTW one. It is also an iterative method, resting on the computation of the DTW alignement between each series and the centroid (the initial one is arbitrarily chosen to define clusters). At each iteration, new centroids are computed by the mean values of series included in each cluster [120]. In the same idea, soft-DTW centroids can be defined [120].
- Shape Extraction (SE): as its name clearly indicates, this methodology rests on the computation and extraction of an average representative series for each cluster. The main idea is the same than DBA expect that mesured distance is computed by the SBD methodology [120], [121].

Once the clusters generated, they have to be analysed to validate them or not. The observation of clusters is difficult and subjective according to the observer and the desired goals. The most current factor of analysis is **the Squared Sum Error (**SSE**)** over all clusters. In this case, (4.4) is generalised in the case where "error" means the distance between an object and its centroid (no matter how it is computed). Therefore, the SSE allows to measure the distance between objects of a cluster and the centroid of this cluster and must be minimised (see 4.5, [122]).

$$SSE(X,Q) = \sum_{i=1}^{K} \sum_{x_j \in Q_i} \parallel x_j - q_i \parallel^2 \tag{4.5}$$

where $X = [x_1, ..., x_N]$ is the set of data, $Q = [Q_1, ..., Q_K]$ are the clusters, $\parallel \cdot \parallel$ is the euclidian distance and q_i is the centroid of the cluster Q_i.

Lots of other analysis parameters have been developed in the literature (as presented and summarised in [119]). Among those indices, the ones interesting in our case are the ones focusing on the cohesion inside a cluster and the separation between clusters because the goal is to define proper and confident groups of days, as dissimilar as possible. For that purpose, **the silhouette indice (**SIL**)** seems the most appropriate. SIL measures the cohesion thanks to, on one side, the distance between all objects inside a cluster a and, on the other side, the distance between clusters a and b (see 4.6, [119]).

$$SIL(Q) = \frac{1}{N} \sum_{Q_i \in Q} \sum_{x_j \in Q_i} \frac{b(x_j, Q_i) - a(x_j, Q_i)}{max(a(x_j, Q_i), b(x_j, Q_i))} \tag{4.6}$$

where:

$$a(x_j, Q_i) = \frac{1}{|Q_i| \sum_{x_h \in Q_i} d_e(x_j, x_h)} \tag{4.7}$$

$$b(x_j, Q_i) = \min_{Q_l \in Q \setminus Q_i} \left[\frac{1}{|Q_l| \sum_{x_h \in Q_l} d_e(x_j, x_h)} \right] \tag{4.8}$$

The analysis of those factors are also a proper way to define at best the number of clusters for the concerned objects. Indeed, a simple representation of the SSE in function of the number of clusters K often allows to observe a break, synonym of an optimal number of clusters. If less clusters than this number are considered, that would lead to higher SSE values. At this opposite, the use of more clusters would not improve significantly the SSE values.

In the same idea, a SIL repartition allows to observe the density of each cluster, $i.e.$ the repartition of the data inside the clusters, and then to conclude about the relevance of the existence of some clusters.

In this part dedicated to clustering, a monovariate analysis on the available data is performed to define the best distance/centroid computation methodology and to have an idea of the best number of clusters.

Monovariate clustering analysis

The monovariate clustering is the most commonly used methodology. It consists of analysing individually each type of data (load, generation and price profiles). In our case, as the goal is to decrease the number of simulated days over the 20 years of planning, each kind of data must be clusterised in the same number of clusters and therefore, each cluster could be a representative or a typical day to be simulated (as the principle illustrated in Fig. 4.2). The disadvantage of the monovariate clustering is the coordination of the clusters of data, $i.e.$ the way that the clusters are combined and the computation of the probability that one cluster of a kind of data occurs in the same time than one cluster of another kind of data. This problem could be countered by analysing and relating (in terms of probability) all the data together ($e.g.$ create a Markov Chain). However, according to the quantity of data and the period that they are covering, this analysis can be hard to execute. Indeed, there could be no synchronism or not enough data to be properly representative of the companies behaviour over the long-term.

Despite this huge disadvantage, some methodologies can be adapted to the multivariate clustering, allowing the clustering of several kinds of data in the same time. This principle is detailed below in this manuscript, but before, let us see if the monovariate clustering application on the desired data is properly working and which combination of distance/centroid computation methodology is the best. This study is led on 5 kinds of data that could be found in a industrial area: a daily load profile (class 2 previously defined), an industrial load profile (class 1 previously defined), a PV generation profile, a Wind Turbine (WT) generation profile and a day-ahead market price profile. All the available data are analysed (going from 1 to 3 year(s) of data). All data have been normalised, $i.e.$ each time series has been decreased by its mean and then divided by its standard deviation.

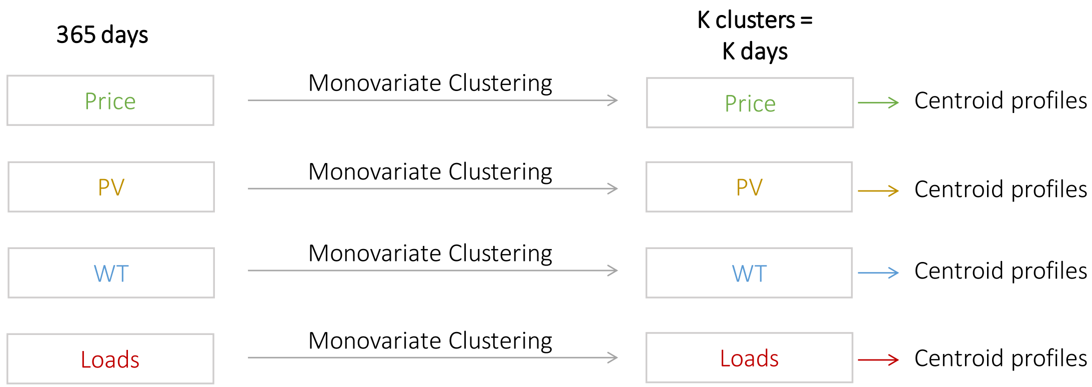


Figure 4.2 – Monovariate clustering application.

For each kind of data the same analysis is realised, based on 3 repetitions of the clustering application (using the *DTWpackage* in the software *R*):

- The analysis of the SIL index to define the two "best" combinations of distance/centroid computation methodologies with the higher SIL values and the lowest CPU time (see Tab. 4.1);
- For the two best methodologies, the SSE is used to define the "best" number of clusters;

	Load Class 1	Load Class 2	PV	WT	Price
DTW	0.2201	0.1853	x	0.2845	0.1109
SDTW	0.3267	0.2448	0.1811	0.4292	0.1900
SBD	0.1905	0.2038	0.1949	0.2391	0.1678
GAK-PAM	0.2951	0.3040	0.3235	0.3759	0.2100
GAK-DBA	0.274	x	x	0.3414	x
L2	0.1588	0.1269	0.1503	0.2235	0.1052

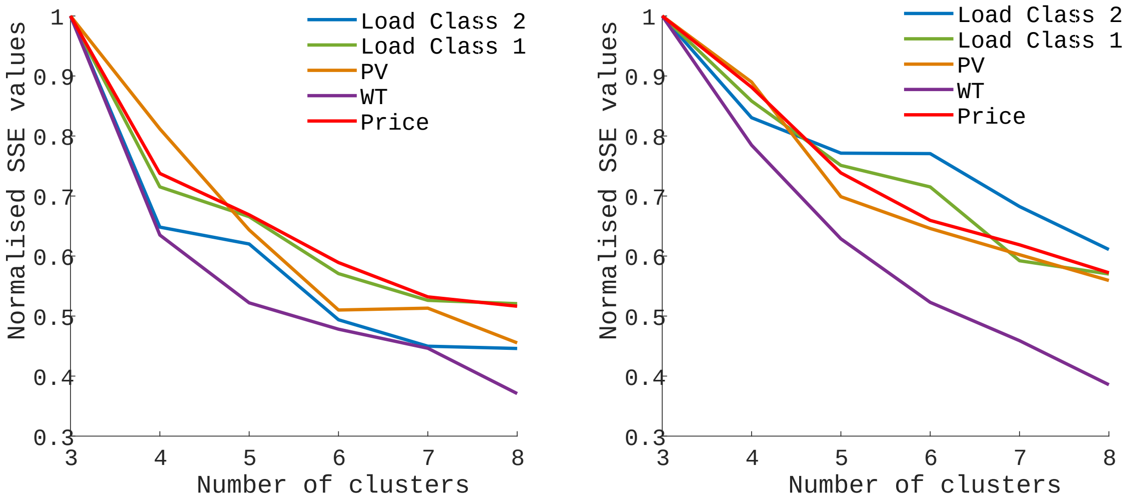
Table 4.1 – Mean SIL analysis over 3 repetitions and 3 to 8 clusters.

The best SIL values are shared between GAK-PAM and SDTW and therefore, these methodologies are kept for the study. Note that regarding simulation times, they are unanimously and significantly lower for GAK-PAM than for SDTW. The crosses in Tab. 4.1 mean that the concerned methodology did not converge for the set of simulation parameters.

The second step of the analysis is to define what is the best number of clusters for each kind of data. For that purpose, as explain before, the SSE can be represented in function of the number of cluster and the break in the curve must be observe for both GAK-PAM (see Fig. 4.3a) and SDTW (see Fig. 4.3b) methodologies.

The breaks are not clearly defined for all data and appear for different number of clusters. With GAK-PAM, the number of 6 or 7 clusters seems the most appropriate for loads and price data, the best value seems to be 6 clusters PV generation and 5 for WT generation. With SDTW, except for the WT (without break), the numbers of 5 or 6 clusters seems the most appropriate. The normalised SSE values are lower with GAK-PAM than with SDTW. **As the GAK-PAM**

methodology can be adapted to used in a multivariate way, is faster and leads to a centroid being part of the real data (*i.e.* medoid), the following multivariate analysis is realised with this methodology.



(a) GAK-PAM (b) SDTW

Figure 4.3 – Number of clusters observation.

Multivariate clustering analysis

Monovariate clustering has been used to analyse the application of clustering on the available data to appoint the distance/centroid methodology and the relevant number of clusters. To apply it to the tool, the multivariate approach has to be used to construct properly the representative days. For that purpose, two approaches can be considered: respectively, *from the top* and *from the bottom* approaches.

From the top approach:

With this first approach, multivariate clustering is applied directly on the available data (as illustrated in Fig. 4.4 and Fig. 4.5). Fig. 4.4 shows the principle of the multivariate distance computation. With monovariate clustering, the individual distances (by the previous methods) were computed for each kind of data. With multivariate, a unique distance is computed for all the data combined, *i.e.* based on a new matrix of data taking into account all the series (as rows). Therefore, the time step and the length of each series must be the same for each variable (*e.g.* 1 year of data).

Once the principle of Fig. 4.4 is applied for all the available days of data (*e.g.* 365 days as in Fig. 4.5), the clustering can be computed in order to decrease the number of days to study to the number of clusters K. Those clusters are attached to one centroid including a daily profile for all kinds of data. **Those centroids are then the representative day profiles to be simulated in the IMG tool.**

In order to see the application of such a clustering, we could observe the centroid shapes of each day. However, the final goal of this application is to see if, after the STEM of the

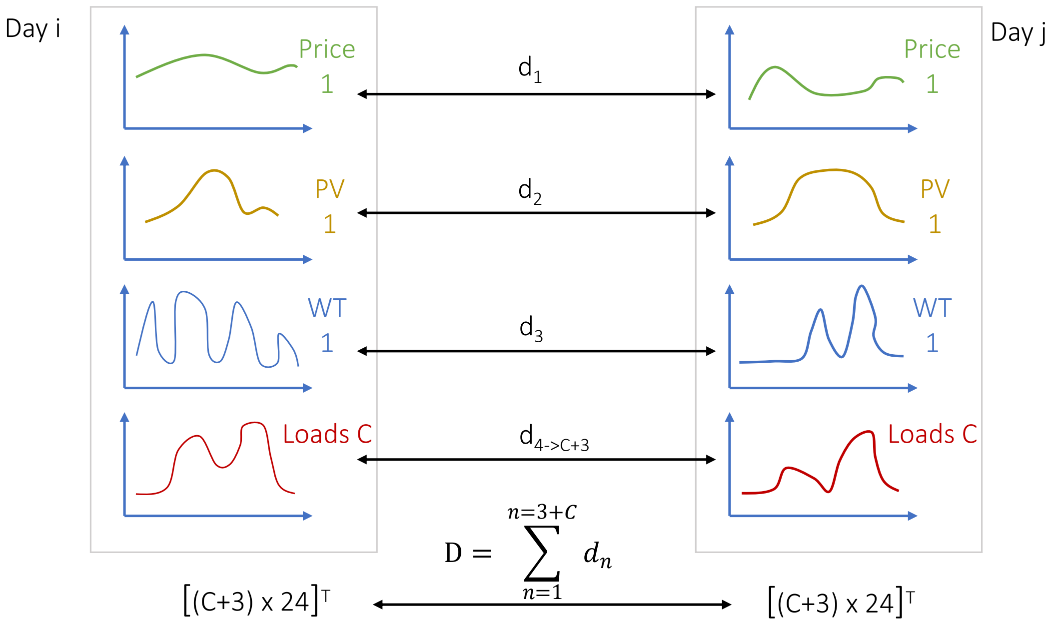


Figure 4.4 – Principle of multivariate clustering.

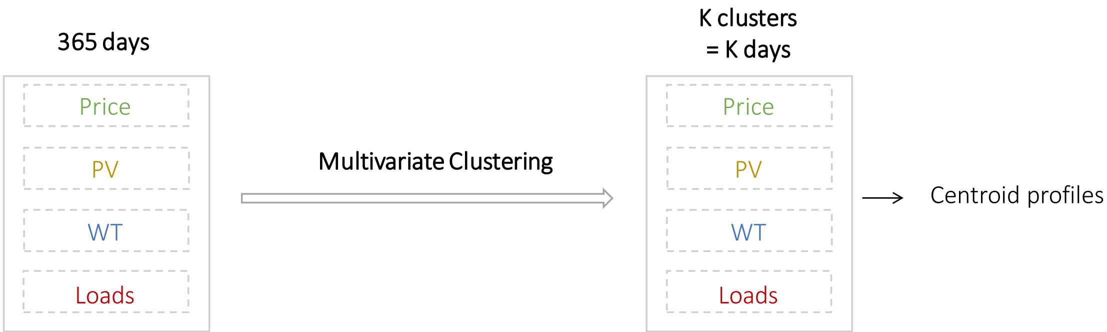


Figure 4.5 – Multivariate clustering application.

developed tool (that can be seen as a *feature transformation* of the initial data), the cash-flows with clustering are congruent with the cash-flows without it.

For that purpose, let us run the STEM for an IMG composed of 3 companies (1, 2 and 3) plus the MGEM and with 6 clusters (*i.e.* days) using load, generation and price normalised data. The methodology GAK-PAM has been used in order to have one real profile as centroid for each cluster. Therefore, the multivariate clustering can be applied and then the only information needed as additional inputs of the developed tool are the belonging to a cluster of each available day of data as well as the day selected as the centroid for each cluster.

Given the cash-flow results shown in Fig. 4.6 - 4.9, the observations are the same for the 4 stakeholders: the existence 6 clusters leads to 6 different cash-flows (different red steps in the figures). However, those values do not capture the peak values of every stakeholders. For example, for the companies 1 and 3 (that are both from class 2), the highest cluster value is just over 0 €, but some of the days in the middle of the year are higher than 100 €. For company 2 (from class 1), the clustering does lead to representative results because real values can be much higher or lower than values obtained with clustering. The results obtained for the MGEM are depending of the other results as his cash-flow depends on the exchanges inside the IMG.

The total cash-flows over the year are computed and obviously lead to bad results:

- Around 40 $k€$ instead of 47 $k€$ for the MGEM;
- Around -70 $k€$ instead of -41 $k€$ for the first company;
- Around -30 $k€$ instead of -71 $k€$ for the second company;
- Around -49 $k€$ instead of -26 $k€$ for the third company.

With a higher number of clusters, results are slightly better but still not representative of one year according to the variability of the daily cash-flows (with the positive and negative peaks).

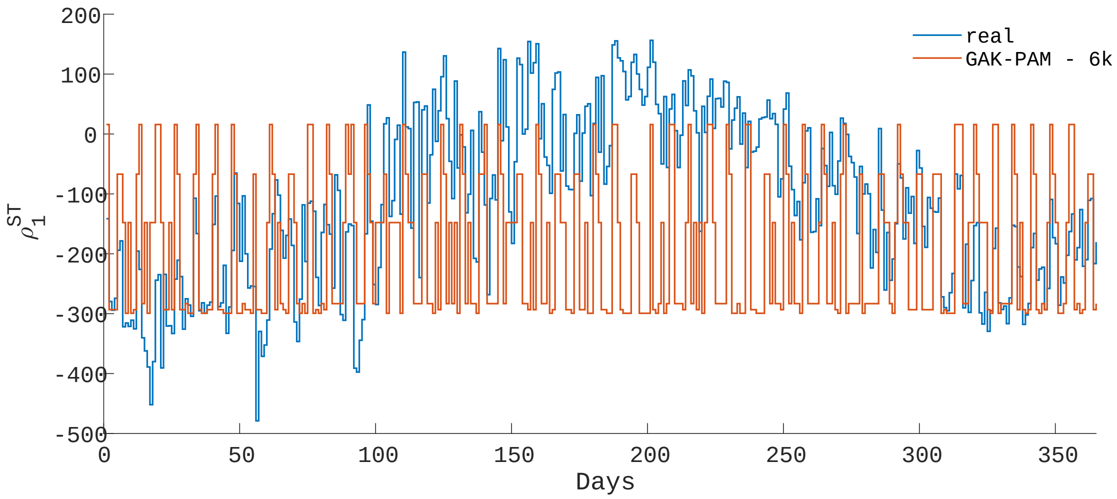


Figure 4.6 – Multivariate clustering on data - Company 1.

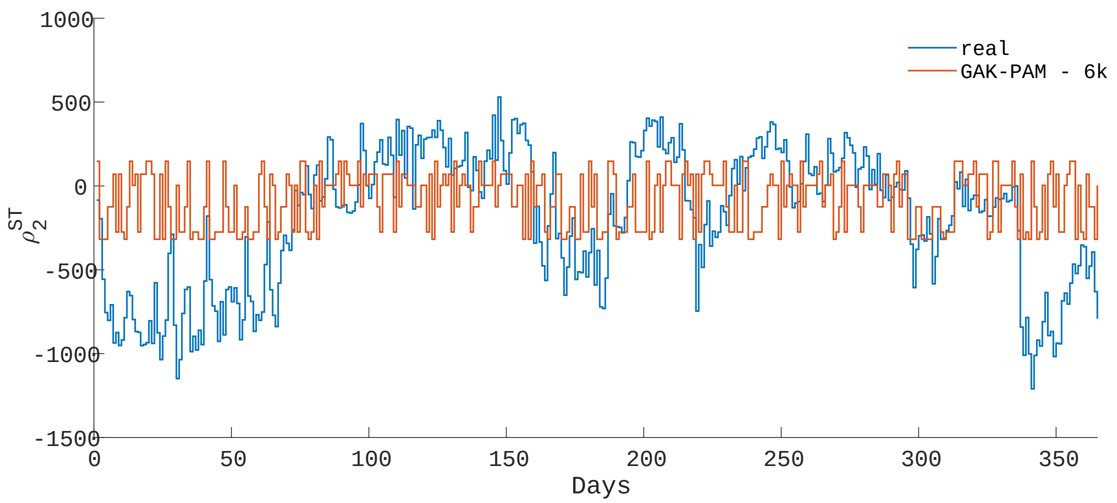


Figure 4.7 – Multivariate clustering on data - Company 2.

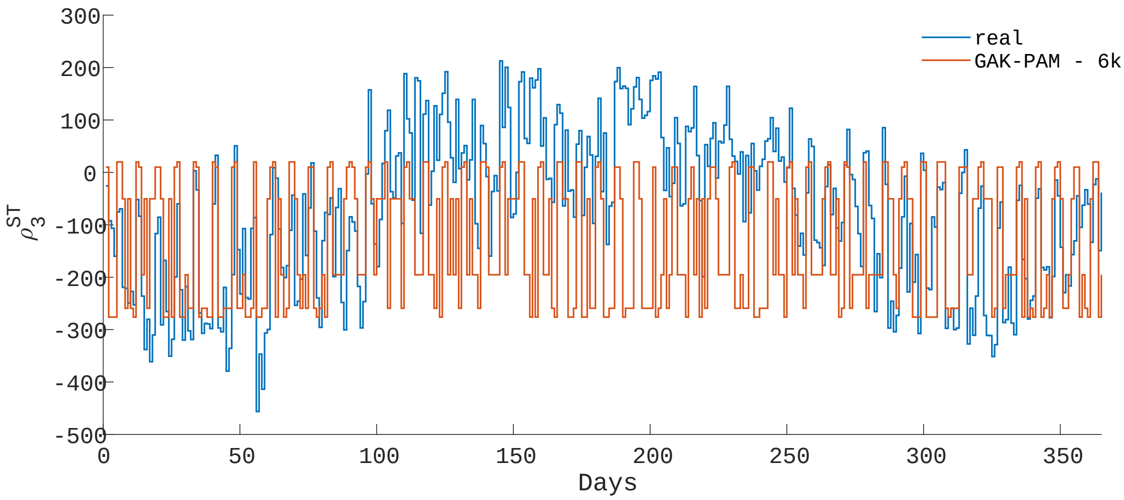


Figure 4.8 – Multivariate clustering on data - Company 3.

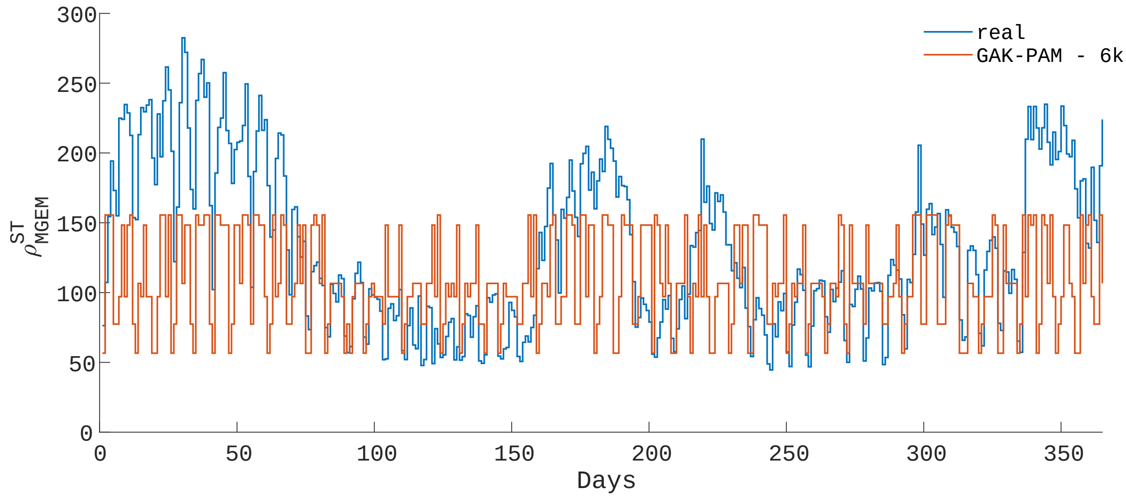


Figure 4.9 – Multivariate clustering on data - MGEM.

From the bottom approach:

Given the relatively bad results of the first approach, the second one *from the bottom* was imagined to see if better results could be achieved. The latter consists of directly applying clustering on the 365 cash-flows obtained by the IMG operation over 1 year of data (loads, generation and price profiles). This second methodology has been applied one the same data than for the first approach and the results are shown in Fig. 4.10-4.13 with again, 6 clusters and the GAK-PAM methodology.

The results are slightly better. Globally, we can see that the trends of the real cash-flows are followed by the clustered ones. However, some important variations and peaks are not captured by the clustering. Regarding the yearly cash-flow obtained, the differences are decreased but still too far from the real values. Moreover, the disadvantage of such a methodology is that the tool needs to be completely simulated over 1 year, which is time consuming. In addition, the extension to the 20 years of planning is not direct.

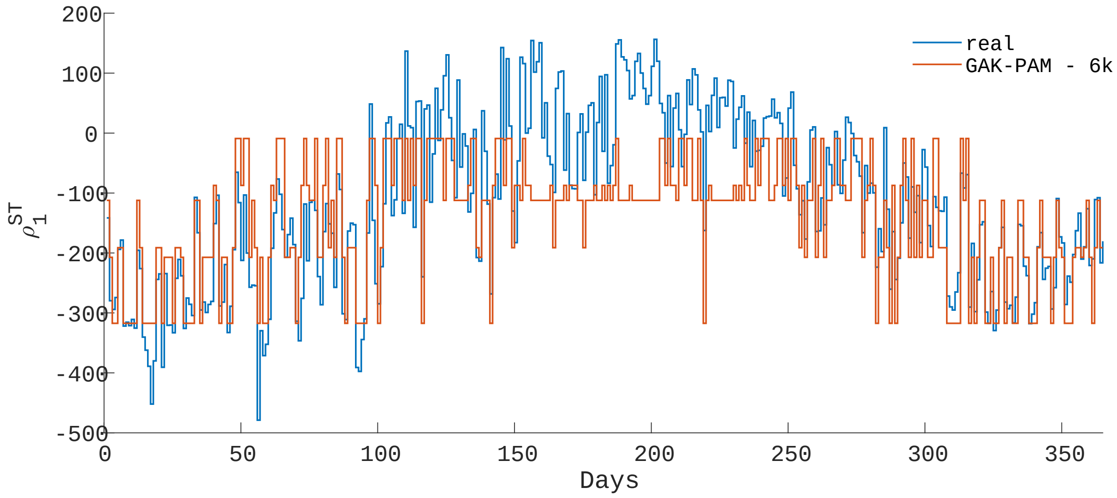


Figure 4.10 – Multivariate clustering on cash-flows - Company 1.

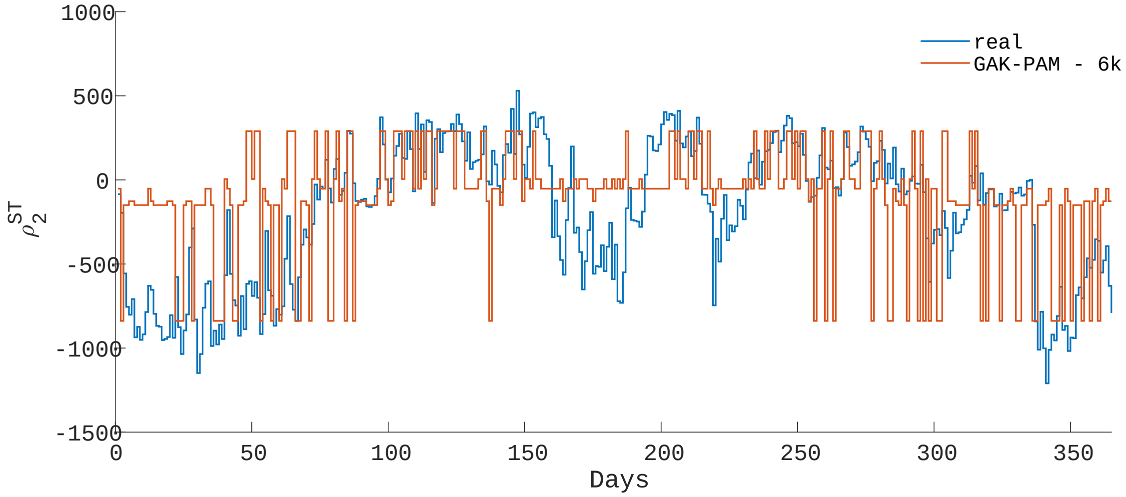


Figure 4.11 – Multivariate clustering on cash-flows - Company 2.

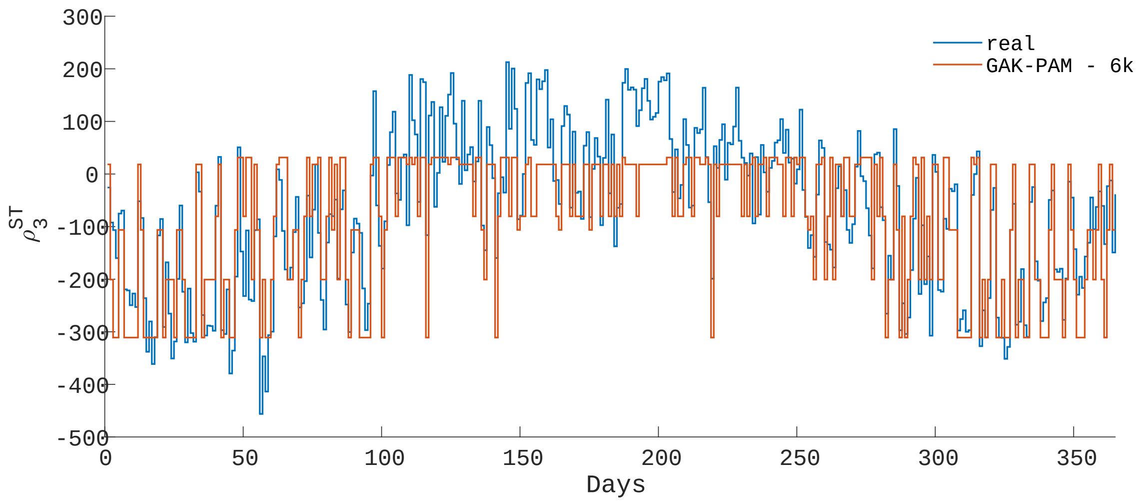


Figure 4.12 – Multivariate clustering on cash-flows - Company 3.

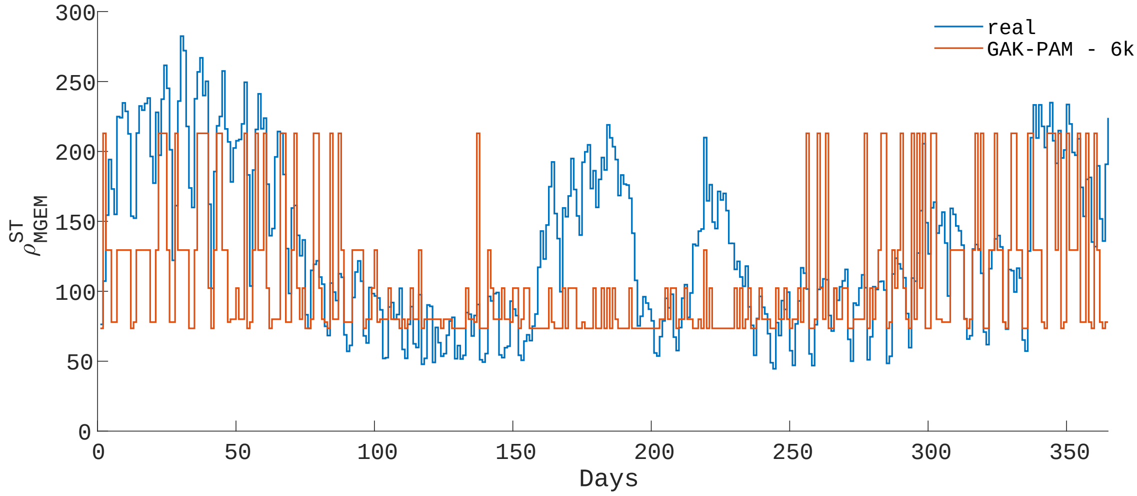


Figure 4.13 – Multivariate clustering on cash-flows - MGEM.

Clustering does not seem to be the most appropriate approach to properly reduce the complexity of the tool. Indeed, the observed results are not enough accurate to be representative of the real behaviour of the IMG. With more stakeholders and decision possibilities in the tool, the truthfulness of the results will not be verified.

The idea of exploring clustering with a huge number of clusters could therefore be considered but the methodology does not guarantee the proper number of clusters and the convergence of the cash-flow results. At this stage of the research, the idea of typical days simulation still seems appropriate but another methodology including the guarantee that the considered days are leading to strong and reliable results should be considered. For that purpose, a global analysis of the data and the convergence of the tool have to be considered, as performed in the following section dealing with Monte Carlo sampling on data distributions.

4.2 Typical days forecasting of load, generation and electricity price using stratified Monte-Carlo on CDFs and PDFs

In order to counter both problems linked to the high number of days to be simulated and the convergence of the tool, the combined use of Probability Distribution Function (PDF), Cumulative Distribution Function (CDF) and Monte Carlo (MC) sampling has been set up. In this section, before going deeper in the application of these methodologies, their definitions and basic principle are exposed.

4.2.1 Definitions: probability distribution functions, cumulative distribution functions and Monte Carlo sampling

A PDF is a non-negative function f_X which describes the probability of a continuous random variable X [123]. The variable X is called normal if its PDF is defined by (4.9). Such a PDF is illustrated in Fig. 4.14a.

$$f_X(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{(x-\mu)^2}{2\sigma^2}} \tag{4.9}$$

where:

- $\mu = \mathbb{E}[X]$ is the mean;
- σ is the standard deviation;
- $\sigma^2 = var(X)$ is the variance;
- e is the natural algorithm.

The CDF of X, F_X, provides the probability $\mathbb{P}(X \leq x)$ and, for a continuous variable, is given by (4.10).

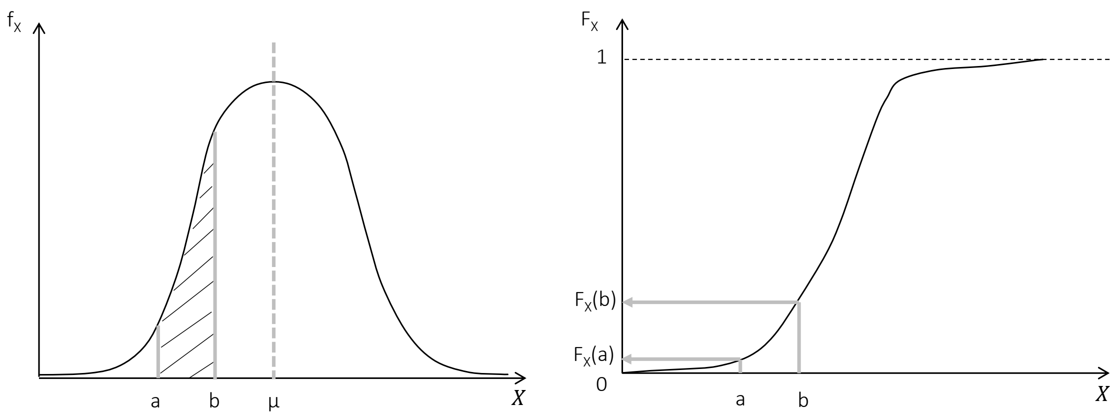
$$F_X(x) = \int_{-\infty}^{x} f_X(u)du \tag{4.10}$$

This definition means that the CDF depicts the accumulated the probability mass up to the value $x \in X$ (see Fig. 4.24a).

Therefore, if a and b are two values from X, the probability related to the area defined by a and b under the PDF represents the probability that x falls between a and b [123]. This probability can be found by both the PDF and the CDF by, respectively, (4.11) and (4.12) and as shown in Fig. 4.14.

$$P(a \leq x \leq b) = \int_{a}^{b} f_X(x)dx \tag{4.11}$$

$$= F_X(b) - F_X(a) \tag{4.12}$$



(a) Normal PDF example

(b) CDF example

Figure 4.14 – PDF and CDF illustrations.

In order to reach a close approximation of an integral computation, MC methods are commonly used. Their goal is to sample the quantity to be estimated by some pseudo-random points

[124]. Mathematically, that means an integration of a function $j(x)$ between 0 and 1 using N samples, which is mathematically expressed by 4.13.

$$\int_0^1 j(x)dn \simeq \frac{1}{N}\sum_{i=1}^{N} j(x_i) \tag{4.13}$$

where $x_i \in X$ (i=1, ..., N) is an uniform law on [0 1].

According to the size of the studied interval, the variance of a MC sampling can be important, which means that a huge number of samples is needed to converge. Different convergence indicators can be used as, for example, the variation factor ε defined by (4.14) for X [125]:

$$\varepsilon = \frac{var(X)/N}{\mu} \tag{4.14}$$

where μ is the mean value of the initial sample set. Another convergence indicator can also simply rely on an approximation of the mean value over the considered interval:

$$\mu \simeq \mathbb{E}[X] \tag{4.15}$$

In order to reduce the variance and so the number of samples , various methodologies are presented in the related literature [124]. Among them, the stratified sampling allows to divide the studied interval into strata and to explore each stratum. Therefore, with stratification, (4.13) becomes (4.16) [126] where N_s is the number of strata ($n_s = 1, ..., N_s$) and z_{n_s} the number of samples per stratum n_s.

$$\int_0^1 j(x)dn \simeq \sum_{n_s=1}^{N_s}\left(\frac{1}{z_{n_s}}\sum_{i=1}^{z_{n_s}} j(x_i)\right) \tag{4.16}$$

Moreover, the stratification methodology used is called proportional, which means that an occurrence probability for each stratum n_s, Δ_{n_s}, has to be defined from the initial data sample.

As detailed in the literature [127], [128], the mean (μ_{n_s}), the variance ($\sigma^2_{n_s}$) and the convergence indicators of the sampling within a stratum n_s can be computed. In order to obtain an unbiased sampling, the mean μ has to be conserved:

$$\mu = \sum_{n_s=1}^{N_s} \Delta_{n_s}\mu_{n_s} \tag{4.17}$$

As already said, the stratification is used to reduce the sampling variance, and, therefore, the number of strata (and of element per statum) should be properly designed to respect [127], [130]:

$$\frac{1}{N}\sigma^2 \geq \sum_{n_s=1}^{N_s} \frac{1}{z_{n_s}}\Delta^2_{n_s}\sigma^2_{n_s} \tag{4.18}$$

where N is the number of samples without stratification. For more readability, the second term of (4.18) will be denoted $\Sigma^2_{n_s,s}$.

In order to study the stratified Monte Carlo in a clearer way, let us directly see its application on PDFs and CDFs.

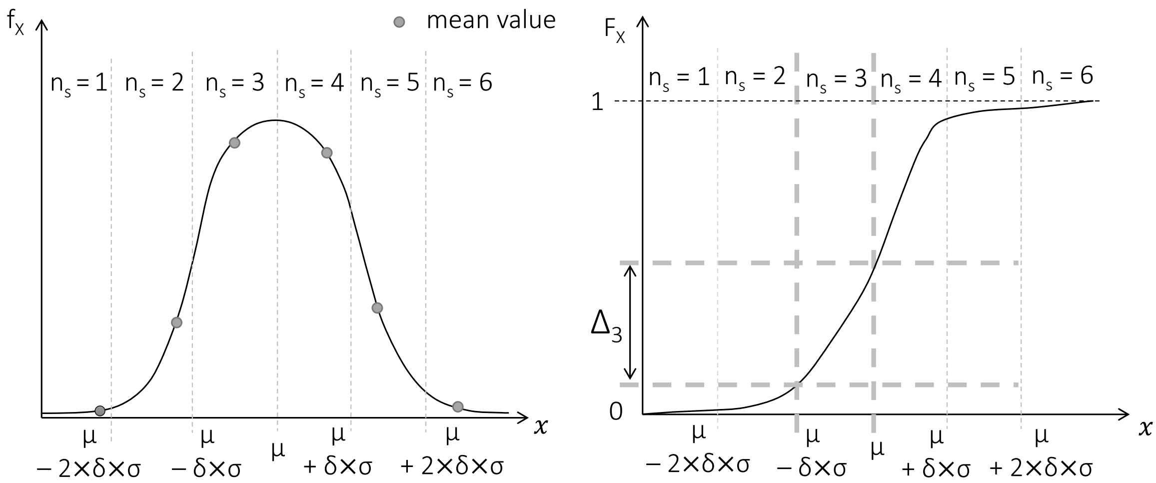
4.2.2 Stratified Monte Carlo sampling on PDF and CDF

In a classical way, the MC sampling is performed on the CDF F_X by the generation of random variables between 0 and 1 and taking the reverse of the CDF to find the corresponding $x \in X$ value [129].

According to the set of data studied, some extreme values (and then the extreme regions of the PDF) could not have been explored leading to non-representative sampling and/or to a huge number of samples needed to access them. The stratification consists of dividing the PDF into smaller regions, called strata, in order to better explore all regions of the PDF and then to guide the sampling in order to reduce its variance.

The PDF stratification principle is shown in Fig. 4.15b with strata that have the same size. The latter is a multiple δ of σ, starting from the mean value. The value of δ will be a parameter to analyse during the validation of the methodology. In this example, the total number of strata is equal to 6 ($n_s = 1, ..., N_s$ with $N_s = 6$).

Therefore, as explained in [129], if we consider the interval $[\mu - \delta \times \sigma; \mu]$, the normal MC sampling has to be done in the interval $[f^{-1}(\mu) ; f^{-1}(\mu - \delta \times \sigma)]$ and the corresponding x values are then found. Within each stratum, the convergence indicators (4.14 and 4.15) are computed using those sampled x values. Moreover, the occurrence probability of each stratum Δ_{n_s} can be defined thanks to the CDF by making the difference between the corresponding stratum bounds, as shown in Fig. 4.15a for the stratum 3.



(a) Normal PDF stratification example (b) CDF stratification example

Figure 4.15 – Stratification principle.

Finally, global convergence indicators, as well as the global mean and variance, can be computed by weighting every stratum values by their attached probability.

4.2.3 Application of stratified MC to the data in the tool context

As already implemented in the small tool, the modelling of load and PV generation data can be realised through the use of their hourly CDFs. In that way, 7×24 CDFs have already been computed. In the first version of the tool, the convergence of the sampling was not checked because the assumption was done that 365×20 samplings for each hour of each day were representative of the reality (and one sampling was equal to one simulated hour). However, this assumption has not been verified yet. Moreover, a lower number of iterations than the initial number of samplings may be enough to converge.

For that purpose, the methodology (divided into two parts) described below in this section is applied and then used in the new version of the tool:

- **The application part** consists of studying the stratification feasibility and checking the properties defined above on the available load and PV generation data. The mean representative value of each stratum as well as its occurrence probability are defined and conserved;
- **The use part** consists of using the strata means and probabilities to generate typical days of simulation. On these days, the STEM is applied, leading to a daily cash-flow for each stakeholder. The final goal of this part is to converge to stable mean values of all stakeholders cash-flows, for the seven days of the week. At the end of this part, the number of simulated days will be checked in order to see if the developed methodology is efficient or not.

Stratification application on data

As in the previous tool, PV generation and load profile of class 2 are sorted by hours and by days (Monday to Sunday). For each stakeholder and for the PV generation and for each hour of each day, a PDF and a CDF are built. The stratification is applied as presented in the previous section. Its goal is to compare the number of iterations needed to converge at a fixed value of ε (in %) without and with the stratification. For that purpose, the value of δ is studied in order to meet at best this objective.

For this study, a **small IMG composed of** 3 **companies (**$C = 3$**) with load profiles of class 2** has been considered. Four simulations are realised:

- Simulation 1: $\varepsilon = 4\%$ with $\delta = 1$;
- Simulation 2: $\varepsilon = 4\%$ with $\delta = 2$;
- Simulation 3: $\varepsilon = 2\%$ with $\delta = 1$;
- Simulation 4: $\varepsilon = 2\%$ with $\delta = 2$;

For each simulation, three comparisons are presented:

- For each day d, the number of iterations needed to converge to the desired value of ε without stratification I_d and with stratification $I_{strat,d}$ (those numbers are defined for the whole IMG, and so there is one value per day, see Tab. 4.2, 4.3, 4.4 and 4.5). As a sampling is performed for each hour h of each day d and for each stakeholder s, $I_{strat,d}$ is defined for d as the maximum number of iterations among all hours and all stakeholders;

- For each day and each company c, the global variance with stratification $\Sigma_{s,c}^2$ is compared to the variance σ_c^2/N without stratification (with N samplings);
- For each day and each company c, the global mean with stratification $\mu_{s,c}$ is compared to the real mean μ_c.

Regarding the results presented in Tab. 4.2, 4.3, 4.4 and 4.5, the use of a higher value of δ clearly reduces the number of iterations to converge to the wished value of ε, which makes sense. The CPU times are all relatively small, given that this operation needs to be realised only once on the available data.

d	1	2	3	4	5	6	7
I_d	950	1203	1226	1053	1231	517	492
$I_{strat,d}$	26	30	30	31	27	40	32

Table 4.2 – Simulation 1 - CPU time: 19.8 s.

d	1	2	3	4	5	6	7
I_d	851	1132	1156	1117	1127	540	462
$I_{strat,d}$	15	18	22	12	19	12	10

Table 4.3 – Simulation 2 - CPU Time: 29.5 s .

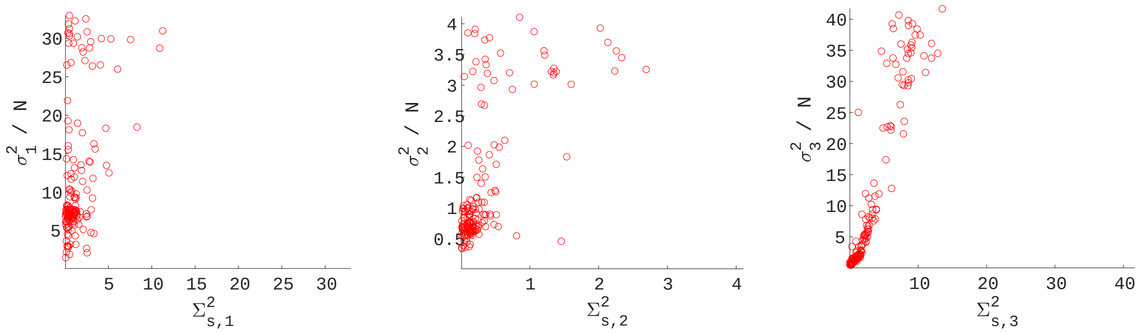
d	1	2	3	4	5	6	7
I_d	3742	4749	4536	4045	4387	2109	1762
$I_{srat,d}$	113	126	125	112	123	143	117

Table 4.4 – Simulation 3 - CPU time: 63.5s.

d	1	2	3	4	5	6	7
I_d	3823	4680	4873	4049	4295	2048	1628
$I_{strat,d}$	64	56	79	67	69	41	41

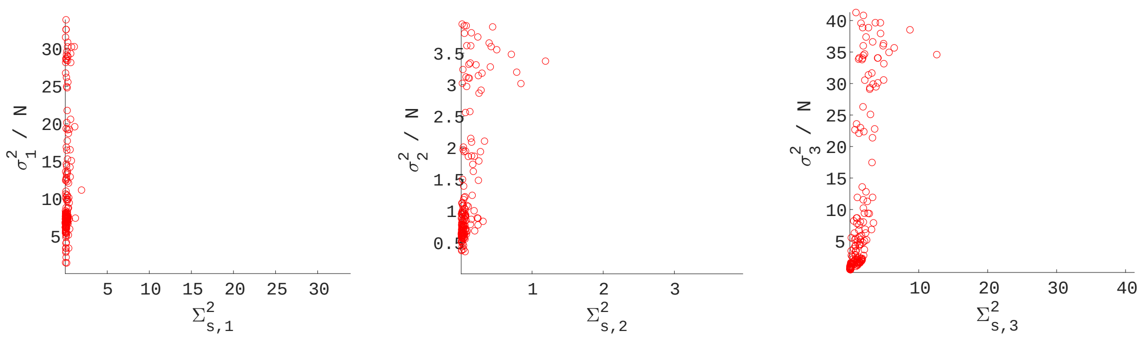
Table 4.5 – Simulation 4 - CPU Time: 74.2 s.

Regarding the comparison of mean and variance values between real data and data built with stratification, all points (24 hours $\times$ 7 days = 168 points) are presented in the same figure in order to observe the global trend of the results. Regarding the variance (Fig. 4.16, 4.17, 4.18 and 4.19), we can observe that, with stratification, it is decreased compared to the approach without stratification. This decrease is more significant with the highest value of δ, *i.e.* for simulations 2 and 4. That means that the stratification allows to obtain less variable samples and, therefore, the number of iteration to reach the convergence should be decreased.



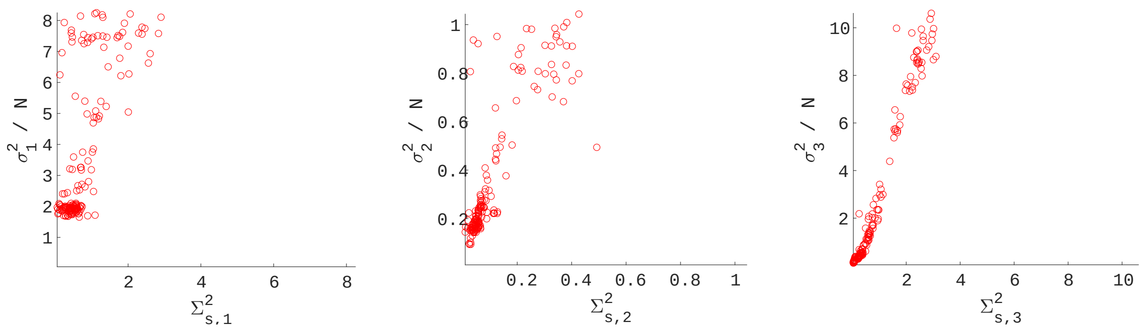
(a) Company 1. (b) Company 2. (c) Company 3.

Figure 4.16 – Simulation 1 - variance without and with stratification comparison.



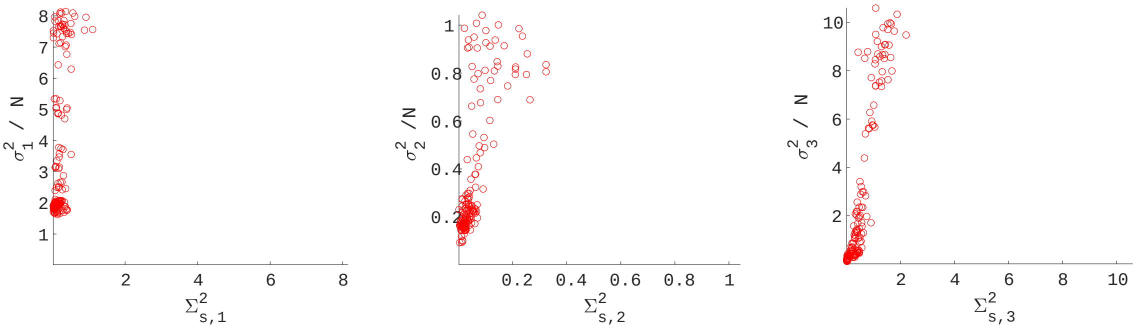
(a) Company 1. (b) Company 2. (c) Company 3.

Figure 4.17 – Simulation 2 - variance without and with stratification comparison.



(a) Company 1. (b) Company 2. (c) Company 3.

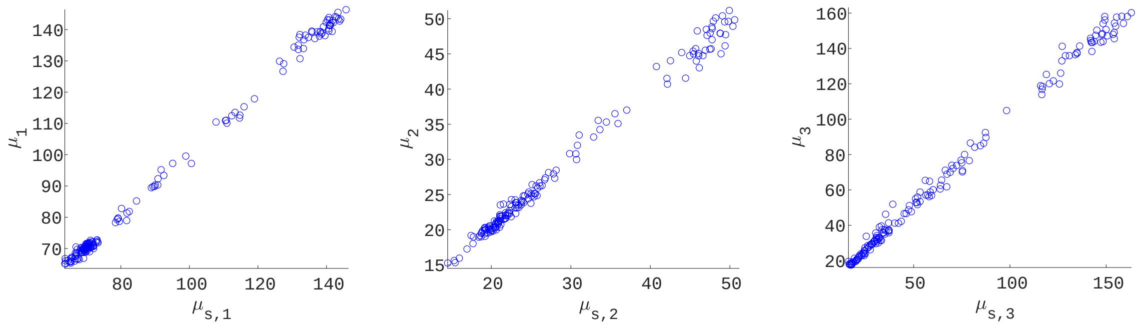
Figure 4.18 – Simulation 3 - variance without and with stratification comparison.



(a) Company 1. (b) Company 2. (c) Company 3.

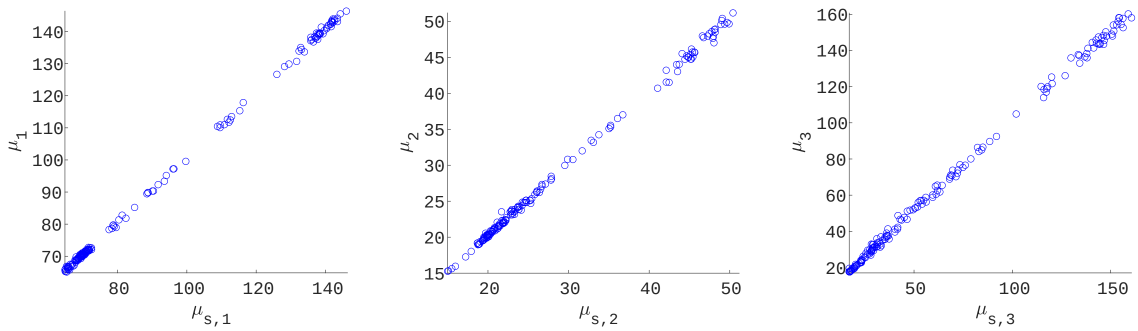
Figure 4.19 – Simulation 4 - variance without and with stratification comparison.

In order to build at best the typical days, the mean value needs to be as close as possible from the real mean value. Observing Fig. 4.20, 4.21, 4.22 and 4.38, that means that the points must be as aligned as possible with the straight of slope equal to one (*i.e.* the diagonal). Clearly, the worst result is observed for the first simulation. Simulations 2 and 3 lead to similar better results and simulation 4 presents the best ones. Those observations also seem obvious given that the ε value is smaller for simulation 4 implying more strata and thus a more accurate value of the built mean value. All those comments are applicable to the three load profiles considered.



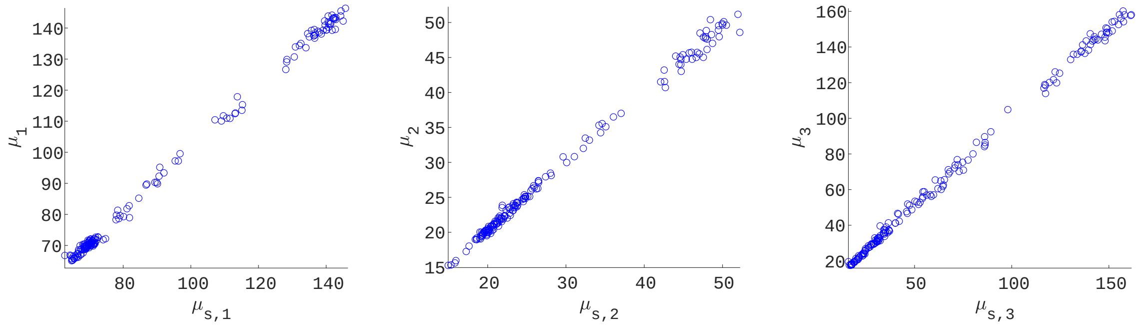
(a) Company 1. (b) Company 2. (c) Company 3.

Figure 4.20 – Simulation 1 - real mean and mean with stratification comparison.



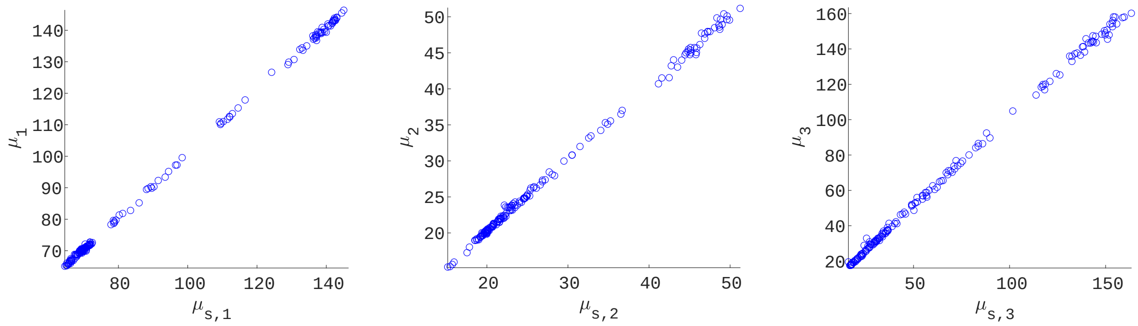
(a) Company 1. (b) Company 2. (c) Company 3.

Figure 4.21 – Simulation 2 - real mean and mean with stratification comparison.



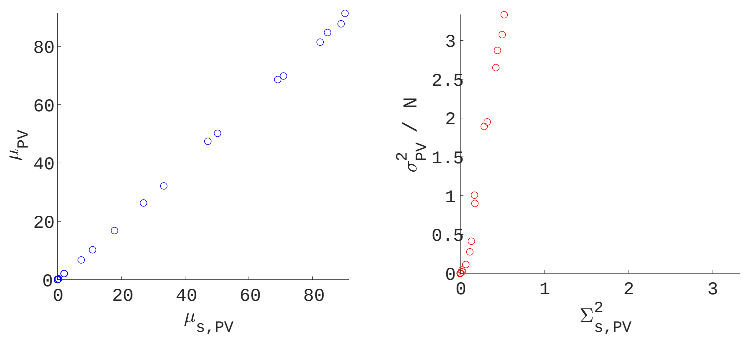
(a) Company 1. (b) Company 2. (c) Company 3.

Figure 4.22 – Simulation 3 - real mean and mean with stratification comparison.



(a) Company 1. (b) Company 2. (c) Company 3.

Figure 4.23 – Simulation 4 - real mean and mean with stratification comparison.



(a) Real mean and mean with stratification comparison.

(b) Variance without and with stratification comparison.

Figure 4.24 – Simulation 4 for PV generation.

The same principle can be applied for the PV generation. In order to check the methodology validity, simulation 4 has been applied for these profiles. For the PV generation, days are not separated, given the independence between the day of the week and the sunshine. Only 24 points are compared for the mean as well as for the variance values with and without stratification. The number of iterations without stratification I_{prod} is higher than 7300 (upper bound authorised for the number of iterations by the tool). With stratification, the number of iterations $I_{strat,prod}$ is decreased to 37. As for the loads, with $\varepsilon = 2\%$ and $\delta = 2$, the variance is well reduced and the mean value for each hour with stratification is close to the real one (see Fig. 4.24).

Typical days generation using stratification information

In order to manage the construction of typical days inside the developed planning tool via the flowchart presented in Fig. 4.25, four informations need to be saved from the stratification application:

1) The number of strata of each hour, each day for each stakeholder and the PV generation;
2) The occurrence probability for each concerned stratum;
3) The mean value of each concerned stratum;
4) All $I_{strat,d}$ and $I_{strat,prod}$ values.

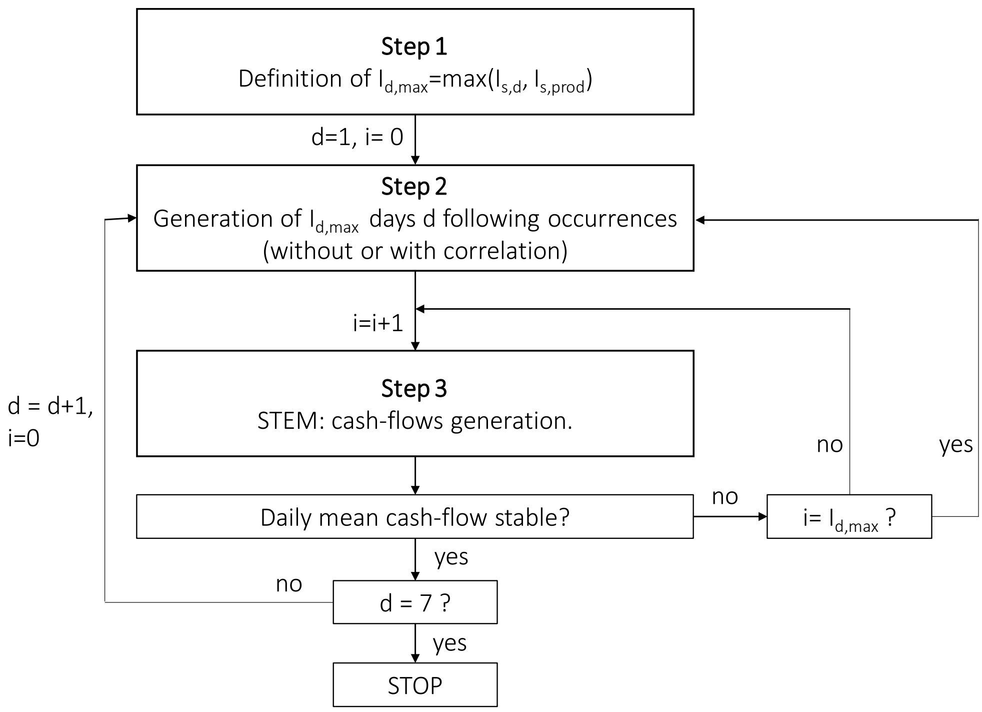


Figure 4.25 – Flowchart of the generation of typical days and mean daily cash-flows.

The **step 1** simply consists of defining, for each day d, the maximum number of iterations between the loads and the generation number of iterations with stratification.

The **step 2** consists of sampling, according to their occurrences, a stratum for each stakeholder and for each hour of the day. This step is a little bit more complex given that two ways of proceeding can be considered: without and with correlation between stakeholder. Without correlation, the occurrence probability of each stratum of each stakeholder (for each day d and hour h) previously defined is directly used to build the $I_{d,max}$ days. If the correlation is taken into account, *joint stata probabilities* need to be defined, as illustrated in Fig.4.26 for a simple example with only two stakeholders.

The principle of the generation of *joint strata probabilities* consists of directly using the available load data of the considered stakeholders. In Fig. 4.26, for two stakeholders, some data are presented for one hour. For this hour, a sample of 20 couples of real data is available. For each stakeholder, the stratification was applied and 6 strata were defined for each one. That means that there will be $6\times6 = 36 = N_{js}$ joint strata to analyse. For each one $n_{js} = 1, ..., N_{js}$, the probability $\Delta_{n_{js}}$ than a couple of data belongs to it is computed. For example, for the joint stratum 1 ($n_{js} = 1$), the attached probability is $\Delta_1 = 1/20 = 5\%$; for $n_{js} = 16$, $\Delta_1 = 3/20 = 15\%$; for $n_{js} = 31$, $\Delta_{31} = 0/20 = 0\%$, and so on. Those new probabilities are then used for the days construction if the correlation is applied.

Note that, each built day also needs to be attached to an electricity price profile. For that purpose, in the same idea, clustering is applied on all available data from the spot market (as in chapter 3) and a probability is attached to each one. For each day, a cluster is selected according to its occurrence and a price profile belonging to it is uniformly randomly selected.

The **step 3** consists, for each day, to apply the STEM in order to generate, for each stakeholder s and for each built day $i = 1, ..., I_{d,max}$, a daily cash-flow $\rho_{d,i,s}$. At each step i, if $i > 1$, a mean daily cash-flow $\rho_{d,s}$ is computed:

$$\rho_{d,s} = \frac{1}{i}\sum_{i}\rho_{d,i,s} \tag{4.19}$$

The loop stops when, for each stakeholder, $\rho_{d,s}$ is stable *i.e.* when its relative value does not change of more then 0.1% in the last 10 iterations (this criterion has been chosen has as compromise between the accuracy of the results and the simulation time).

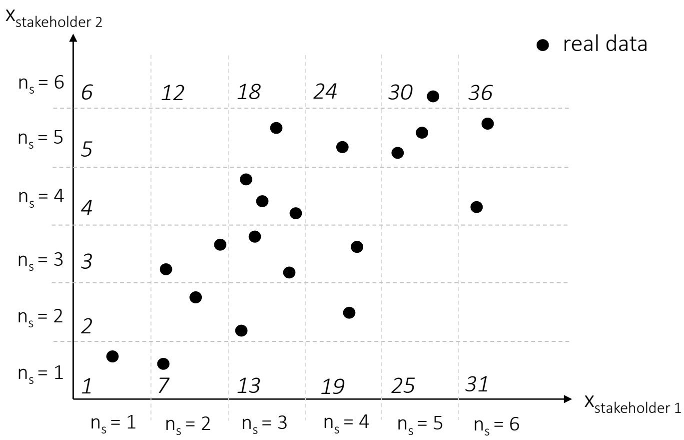


Figure 4.26 – Joint strata probabilities generation for one hour.

In order to validate the described methodology, it is tested on the same small IMG composed of 3 stakeholders and the MGEM (who is still the DSO), without investments (only one LT configuration). It is simulated only over one year in order to compare the generated values with the ones obtained with the corresponding available real data. The simulations are realised with $\varepsilon = 2\%$ and $\delta = 2$. One last issue needs to be analyse regarding the use of the previously saved mean value of each stratum. Indeed, we need to investigate if its use is accurate enough or if it is necessary to make a normal random sampling inside the considered stratum at each iteration (*i.e.* there is 2 samplings for each iteration, one for the number of the stratum and one inside the considered stratum). For that purpose, both simulations are realised in this section via 4 tests:

- Test case 1: without correlation, with sampling inside the considered stratum;
- Test case 2: without correlation, using the mean of the considered stratum;
- Test case 3: with correlation, with sampling inside the considered stratum;
- Test case 4: with correlation, using the mean of the considered stratum.

For each test, the final accumulated cash-flow over one year (52 weeks) is computed by (4.20) for each stakeholder s, in order to be directly compared with the value obtained with real data. The results are presented in Tab. 4.6. The number of iterations to stabilise the mean daily payoff values for each simulation is presented in Tab. 4.7.

$$\rho_s = \sum_{d=1}^{7} 52 \times \rho_{d,s} \tag{4.20}$$

	No IMG	IMG	Test 1	Test 2	Test 3	Test 4
MGEM	29204	39226	41876	41852	43062	42910
c=1	-77966	-72764	-71275	-71291	-72618	-72281
c=2	-24828	-22386	-21842	-21792	-22452	-22403
c=3	-23258	-20227	-18904	-19577	-20272	-20996

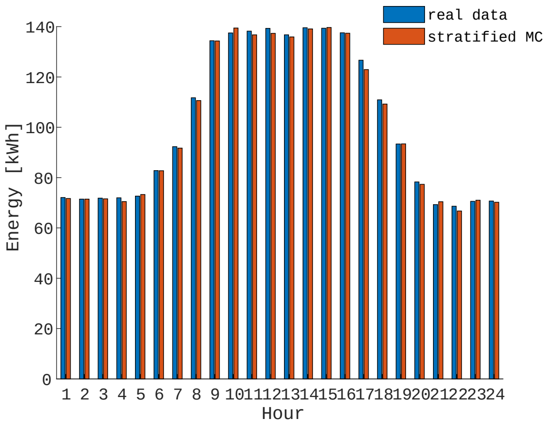
Table 4.6 – Yearly cash-flows for each stakeholder and each test case.

d	1	2	3	4	5	6	7	$\sum$
Test 1	144	213	206	221	280	397	175	1636
Test 2	166	148	189	221	189	249	200	1362
Test 3	208	131	174	142	160	339	269	1423
Test 4	126	148	117	88	165	161	305	1110

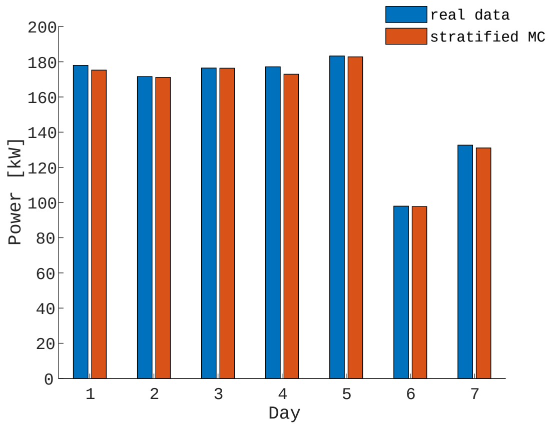
Table 4.7 – Number of iterations to stabilise the mean daily payoff values.

By analysing Tab. 4.6 and 4.7, we can observe that all the obtained cash-flows seem consistent. However, the closer ones occur with correlation, between the stakeholders loads and the PV generation, which makes sense because it allow to go as close as possible of the real data. The use of the mean or the sampling does not lead to significant changes in terms of cash-flows. Regarding the number of iterations, it is reduced thanks to the use of the mean. Another significant point to take into account for the future global tool is the simulation time: for test 3, it is about 66 s and it is only about 10 s for test 4. Therefore, the use of the mean could be more interesting from this point of view for the integration of this methodology in the tool.

Moreover, as the cash-flow mainly depends on the energy and power components, for each stakeholder, the hourly mean values with real and built load data as well as the load peak value of each day with real and built data are compared in the following figures. For more clarity, the mean values of the load are presented only for one day (Monday). We can observe that there are no significant changes between the four tests: they seem consistent with the results in Tab. 4.6.

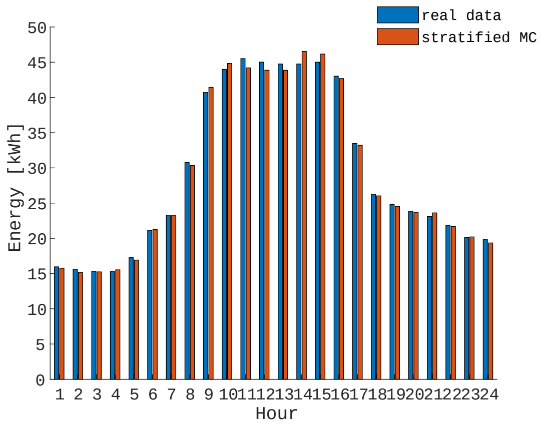


(a) Load mean values - Monday.

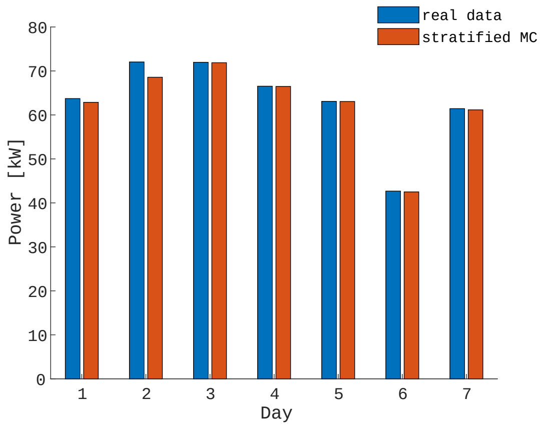


(b) Load peak values.

Figure 4.27 – Test 1 - company 1.

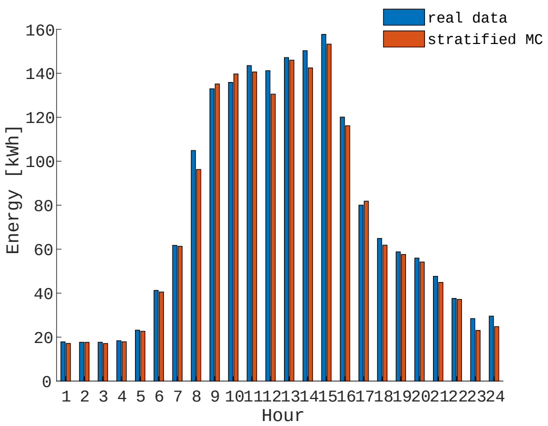


(a) Load mean values - Monday.

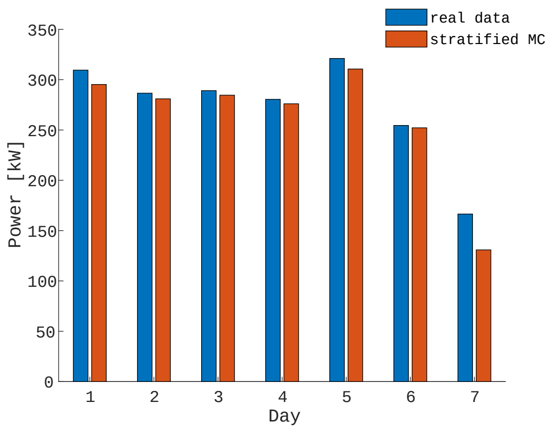


(b) Load peak values.

Figure 4.28 – Test 1 - company 2.

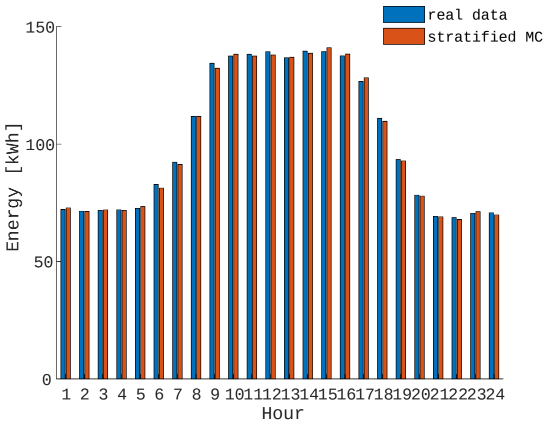


(a) Load mean values - Monday.

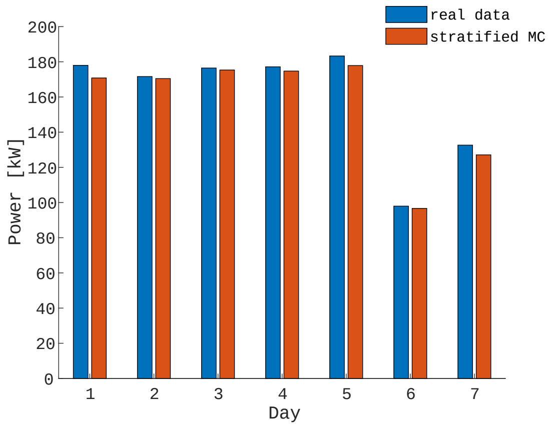


(b) Load peak values.

Figure 4.29 – Test 1 - company 3.

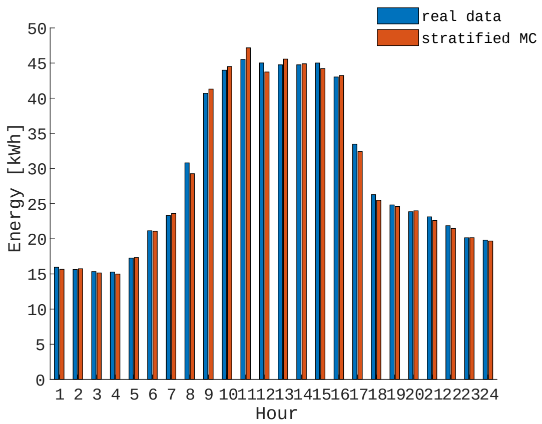


(a) Load mean values - Monday.

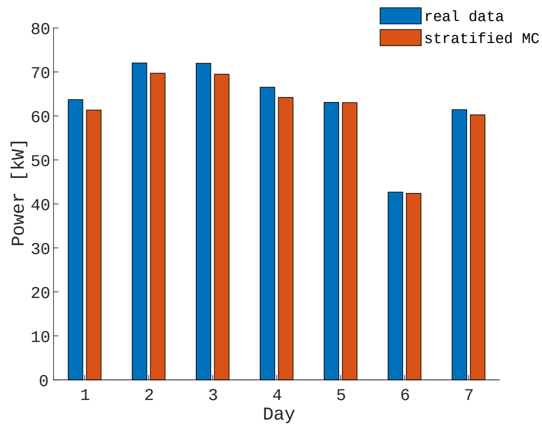


(b) Load peak values.

Figure 4.30 – Test 2 - company 1.

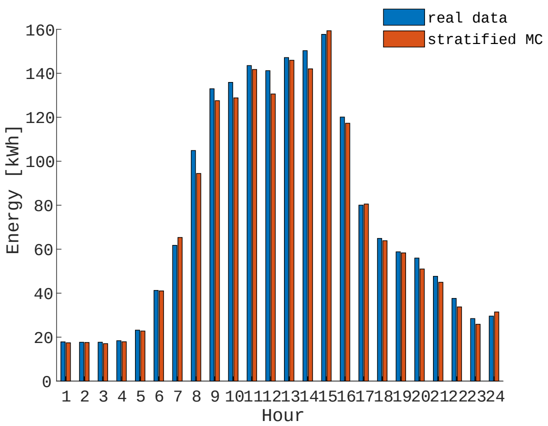


(a) Load mean values - Monday.

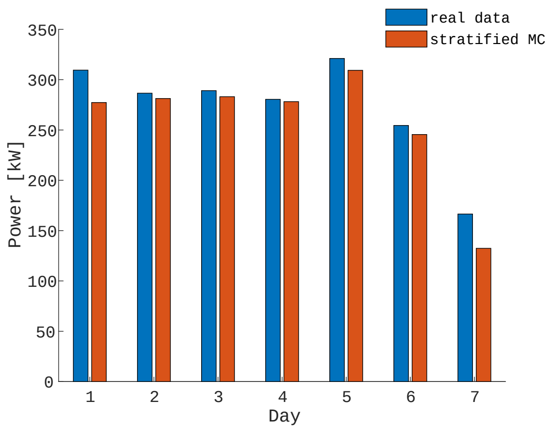


(b) Load peak values.

Figure 4.31 – Test 2 - company 2.

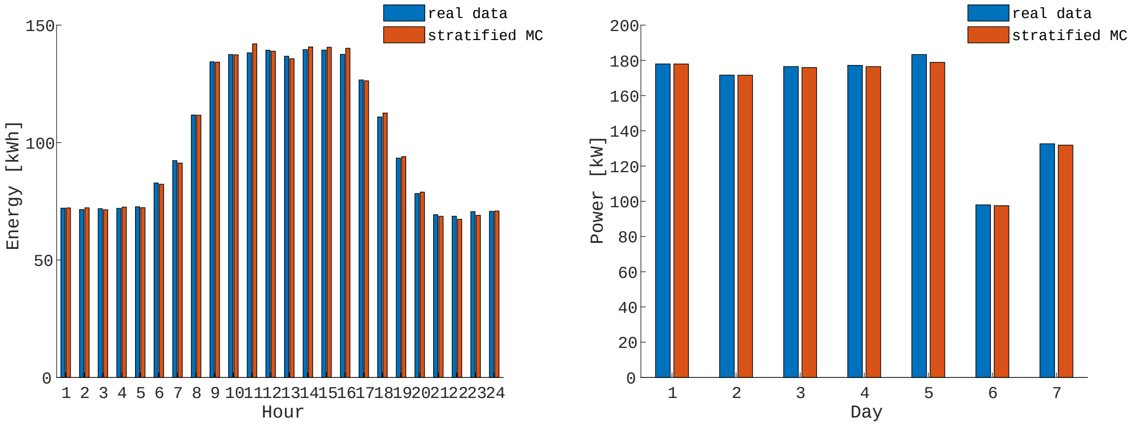


(a) Load mean values - Monday.



(b) Load peak values.

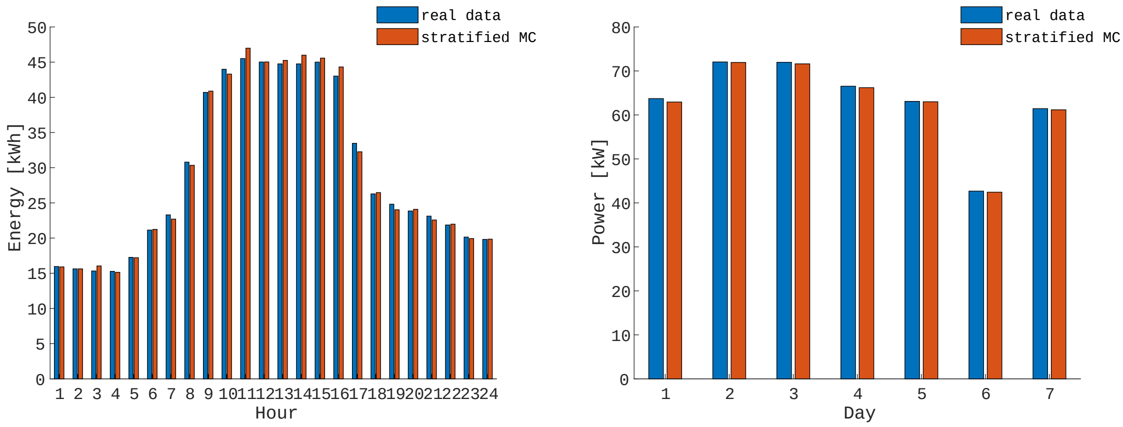
Figure 4.32 – Test 2 - company 3.



(a) Load mean values - Monday.

(b) Load peak values.

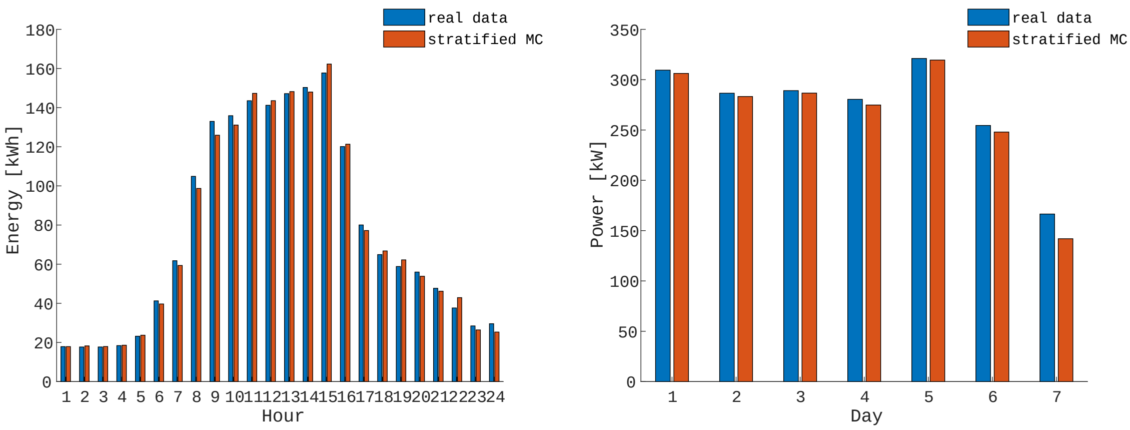
Figure 4.33 – Test 3 - company 1.



(a) Load mean values - Monday.

(b) Load peak values.

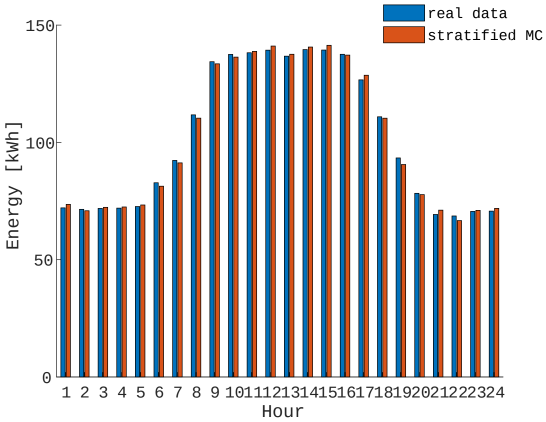
Figure 4.34 – Test 3 - company 2.



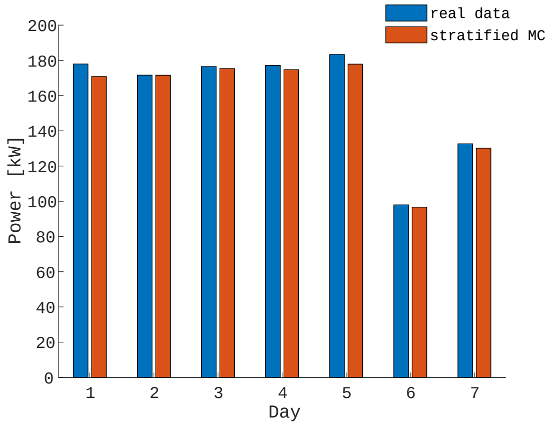
(a) Load mean values - Monday.

(b) Load peak values.

Figure 4.35 – Test 3 - company 3.

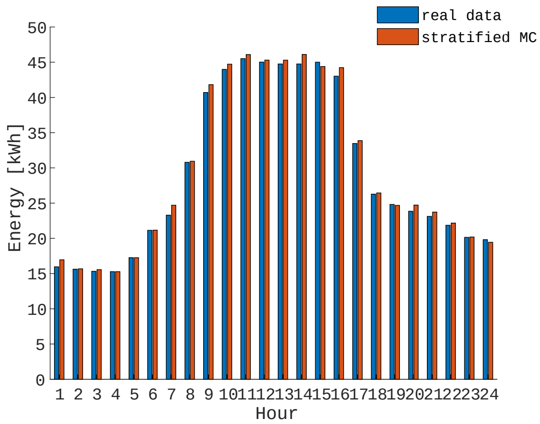


(a) Load mean values - Monday.

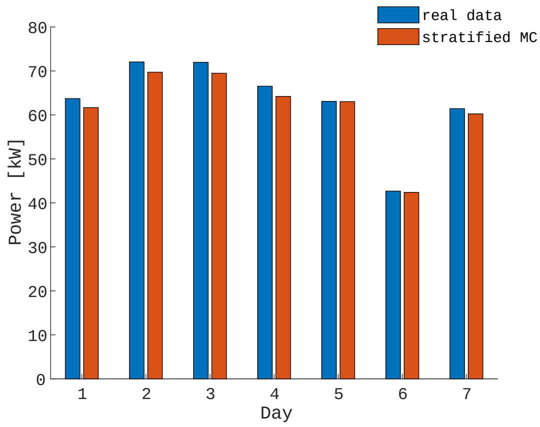


(b) Load peak values.

Figure 4.36 – Test 4 - company 1.

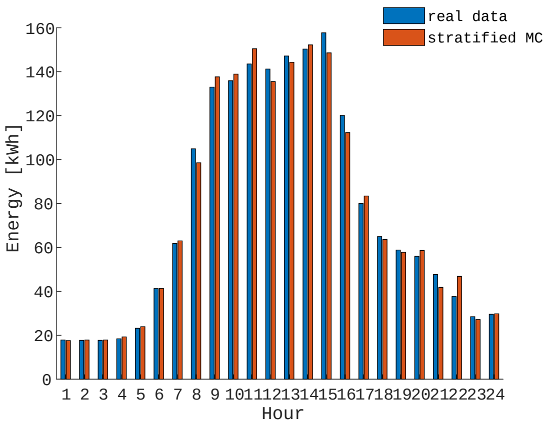


(a) Load mean values - Monday.

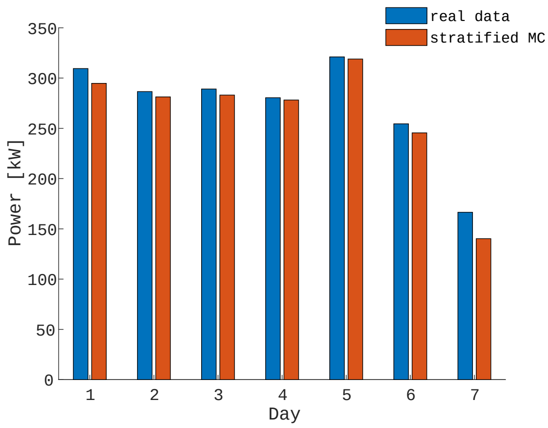


(b) Load peak values.

Figure 4.37 – Test 4 - company 2.



(a) Load mean values - Monday.



(b) Load peak values.

Figure 4.38 – Test 4 - company 3.

4.2.4 Multivariate CDFs and PDFs

Another way to consider the correlation between stakeholders could be to directly build multivariate CDF and PDF among all of them. In [123], detailed definitions and formulas for bivariate and multivariate normal PDFs are given. In this report, let us focus on the PDF expression as well as on the application and interpretation of such PDFs and CDFs.

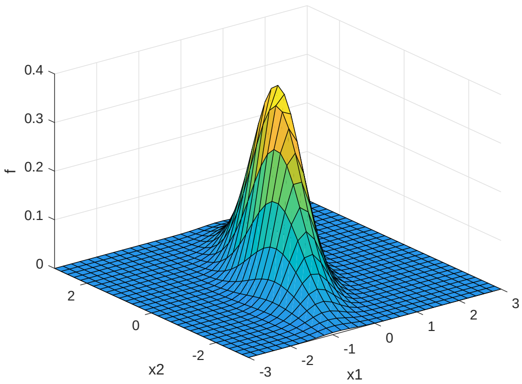
A multivariate normal PDF, for a given vector of p variables realisation, denoted $\mathbf{x} = (x_1, ..., x_p)'$, is defined as [123]:

$$f(\mathbf{x}) = \frac{1}{(2\pi)^{(p/2)}|\mathbf{\Sigma}|^{1/2}} exp\left(-\frac{1}{2}(\mathbf{x}-\boldsymbol{\mu})'\Sigma^{-\mathbf{1}}(\mathbf{x}-\boldsymbol{\mu})\right) \tag{4.21}$$

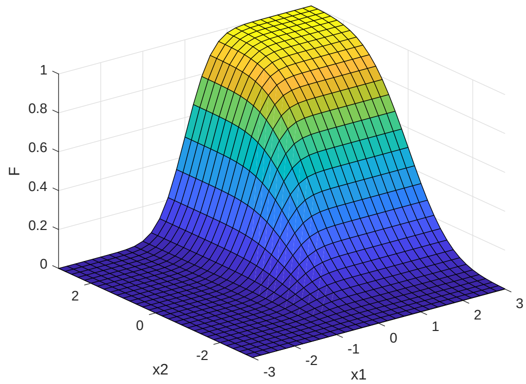
where:

- $\boldsymbol{\mu} = (\mu_1, ..., \mu_p)'$ is the $p \times 1$ mean vector;
- $\mathbf{\Sigma}$ is the $p \times p$ covariance matrix, in which the diagonal elements σ_{jj} are the standard deviations and the other elements σ_{ij} are the correlation coefficients between x_i and x_j, where $x_j \sim N(\mu_j, \sigma_{jj})$ for all $j = 1, ...p$.

In order to develop the principle and the application, a simple example is presented in [131]. Fig. 4.39 shows, the shape of a 2 dimensions (variables x_1 and x_2) PDF (Fig. 4.39a) and CDF (Fig. 4.39b).



(a) Multivariate PDF example



(b) Multivariate CDF example

Figure 4.39 – Multivariate example with 2 dimensions.

Regarding stratification, in this context, a stratum is now a surface of the PDF/CDF. Each stratum is defined by two couples of points: $(x1_{n_s,start}, x2_{n_s,start})$ and $(x1_{n_s,end}, x2_{n_s,end})$. The probability of a stratum n_s can therefore be interpreted as the volume under the surface, $i.e$ as the density into a square defined by $[(x1_{n_s,start}, x2_{n_s,start}); (x1_{n_s,end}, x2_{n_s,end})]$. Fig. 4.40 shows the density projection of Fig. 4.39 as well as the stratum area defined by the couple $[(0,0); (1,1)]$. The occurrence probability of a stratum can therefore be found thanks to the reverse of the CDF (using its density projection).

Before analysing the results obtained with the multivariate PDF and CDF methodology, let us make the point about the pros and cons that already occurs before the simulations:

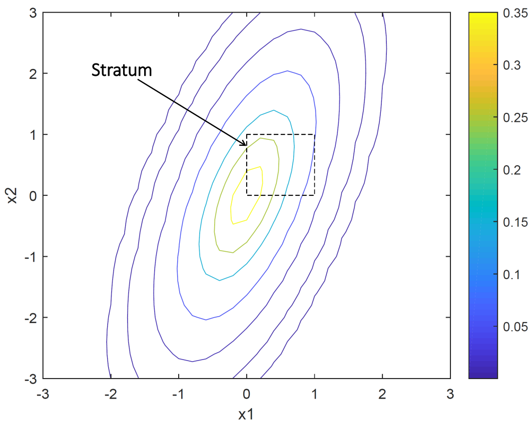


Figure 4.40 – Density projection.

- Advantage: this methodology works for all data and not only for real data values measured in the same time interval (as in the correlation computation methodology defined in the previous section).
- Disadvantage: the built surfaces are quite complex (especially if the monovariate PDF and CDF are not with a perfect shape). Therefore, the surfaces contain lots of vagueness and are difficult to observe and read with more than two variables. In the Matlab function used, it is specified that the probability computed has an estimate error of 1.0000e-08.

A first simulation has been performed in the same conditions than for the monovariate case: $\varepsilon = 2‰$ and $\delta = 2$. The computation time for building the PDF and the CDF with the stratification application is about 25 minutes.

After the generation of typical days using the mean values (methodology approved in the previous section) and application of the STEM, the yearly cash-flows are computed by (4.20) for each stakeholder (see Tab. 4.8). The number of iterations to reach stable mean cash-flows are presented in Tab. 4.9. Moreover, to see the coherence of the methodology, the monday mean hourly load values and to the load peak values of each day for the three stakeholders (Fig. 4.41, 4.42 and 4.43) are observed.

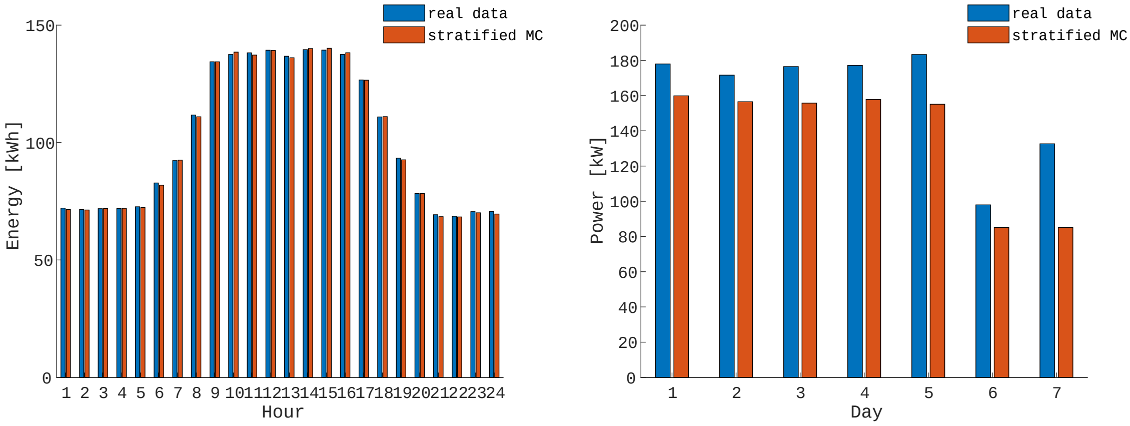
	No IMG	IMG	Simu
MGEM	29204	39226	38796
c=1	-77966	-72764	-72006
c=2	-24828	-22386	-22319
c=3	-23258	-20227	-14354

Table 4.8 – Yearly cash-flows with multivariate simulation ($\varepsilon = 2‰$, $\delta = 2$).

d	1	2	3	4	5	6	7	$\sum$
Multi	56	134	169	180	137	230	103	1009

Table 4.9 – Number of iterations to stabilise the mean daily cash-flows ($\varepsilon = 2‰$, $\delta = 2$).

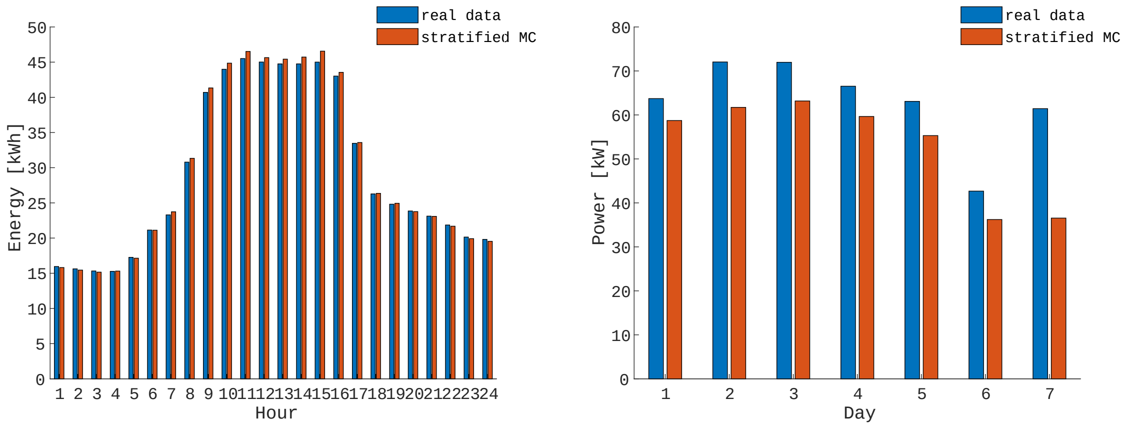
The results in Tab. 4.8 show that, even if the cash-flows are consistent for the MGEM, for the companies, the load peak values are not very consistent with the real ones, especially for



(a) Load mean values - Monday.

(b) Load peak values.

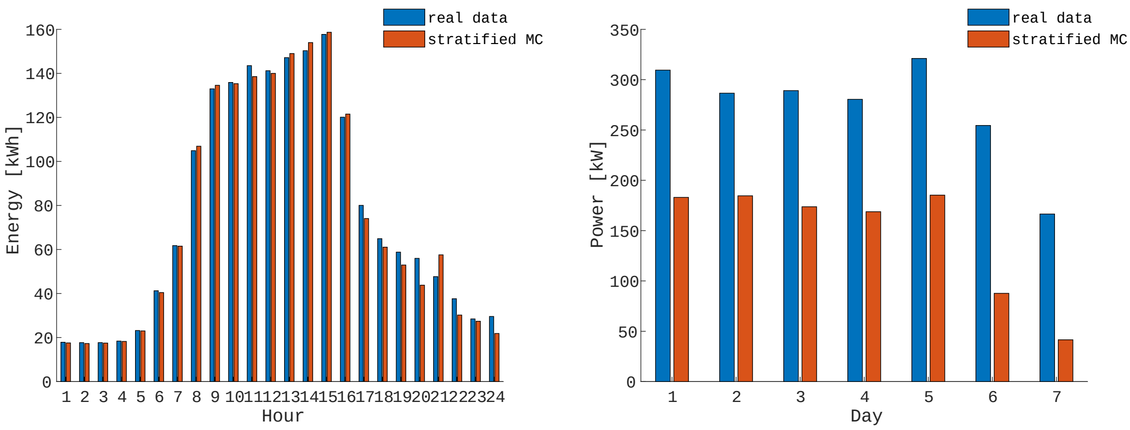
Figure 4.41 – Multivariate simulation - company 1 ($\varepsilon = 2\%$, $\delta = 2$).



(a) Load mean values - Monday.

(b) Load peak values.

Figure 4.42 – Multivariate simulation - company 2 ($\varepsilon = 2\%$, $\delta = 2$).



(a) Load mean values - Monday.

(b) Load peak values.

Figure 4.43 – Multivariate simulation - company 3 ($\varepsilon = 2\%$, $\delta = 2$).

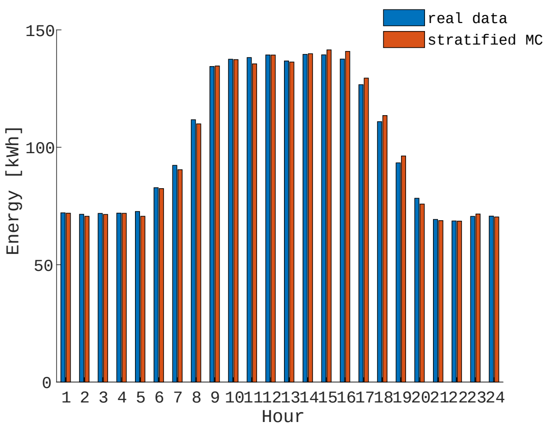
the stakeholder company 3 (which is the only one to own PVs, which probably duplicate the error in the data construction). This can be explained by the probability values of PDF that are very low against to the error value of the function. The strata probabilities defined are possibly wrong and then lead to inconsistent sampling in which extreme values are never chosen and the load peak values are far from the real ones. The solution could therefore to define less strata in order to obtain probability values that make sense against the measurement error. A simulation with $\delta = 0.5$ has been realised to see if this assumption is true. This time, the CPU time is only about 62 seconds.

	No IMG	IMG	Simu
MGEM	29204	39226	40789
c=P1	-77966	-72764	-71932
c=2	-24828	-22386	-22338
c=3	-23258	-20227	-16208

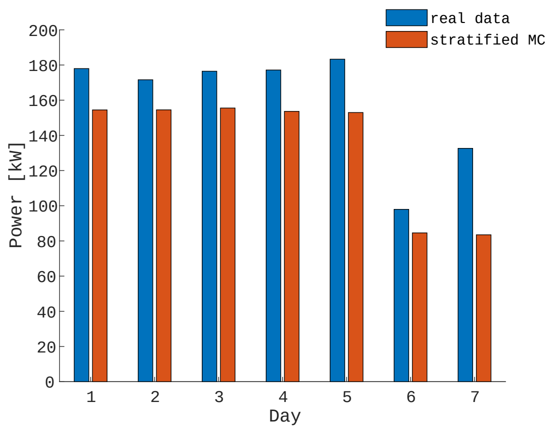
Table 4.10 – Cash-flows with multivariate simulation (ε = 2%, δ = 0.5).

d	1	2	3	4	5	6	7	$\sum$
Multi	205	197	205	204	123	265	141	1340

Table 4.11 – Number of iterations to stabilise the mean daily cash-flows (ε = 2%, δ = 0.5).



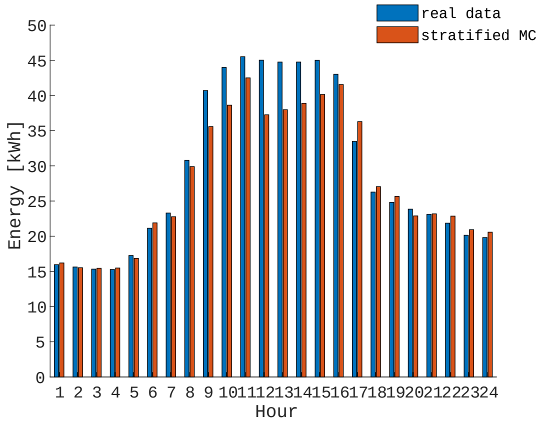
(a) Load mean values- Monday.



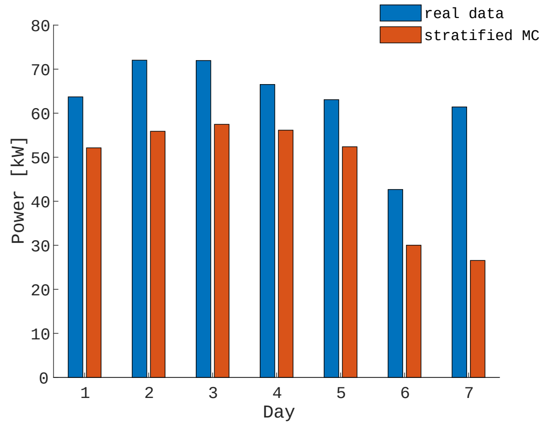
(b) Load peak values.

Figure 4.44 – Multivariate simulation - company 1 (ε = 2%, δ = 0.5).

Results presented in Tab. 4.10, Tab. 4.11 and Fig. 4.44, 4.45 and 4.46 are not drastically changed compared to the previous ones. The number of iterations is increased. This time, as the sizes of the strata are bigger, their respective mean value is less representative of the data inside of them and, therefore, some load peak values are still never reached. For both companies 2 and 3, the mean values are not close from the real ones for Monday. Given that the yearly cash-flow of the company 2 is close from the real ones, that means that other days lead probably the opposite configurations, with higher mean values. It is the case for Tuesday and Thursday, see Fig. 4.47 for example). This means that the results are quite unstable.

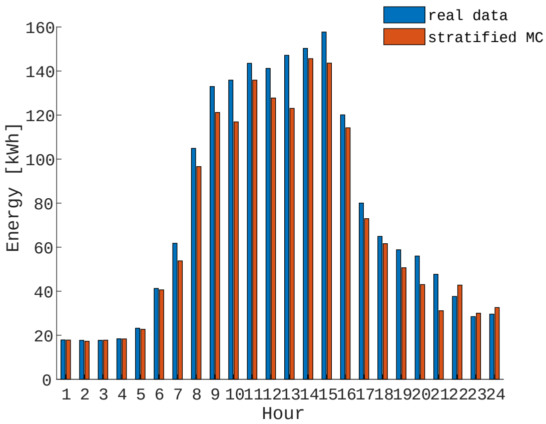


(a) Load mean values - Monday.

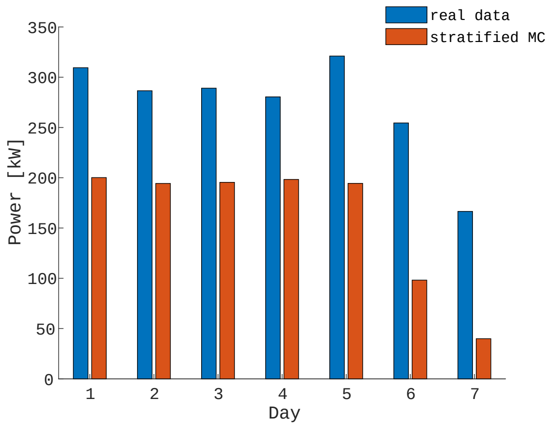


(b) Load peak values.

Figure 4.45 – Multivariate simulation - company 2 (ε = 2%, δ = 0.5).

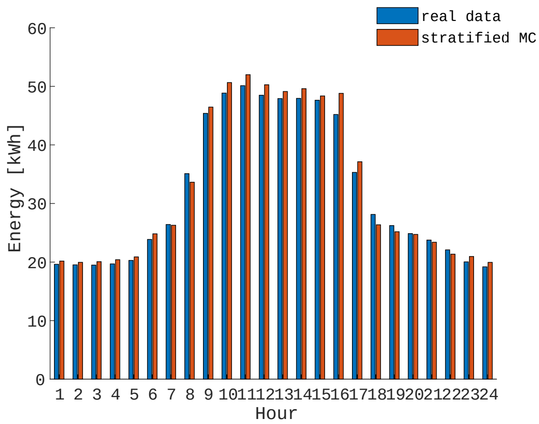


(a) Load mean values - Monday.

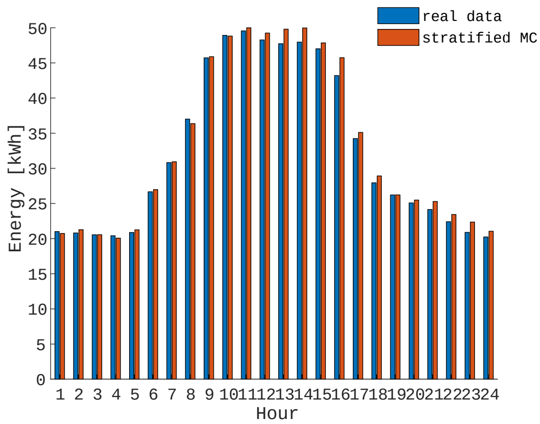


(b) Load peak values.

Figure 4.46 – Multivariate simulation - company 3 (ε = 2%, δ = 0.5).



(a) Load mean values - Tuesday



(b) Load mean values - Thursday

Figure 4.47 – Multivariate simulation - company 2 (ε = 2%, δ = 0.5).

4.3 Conclusion

This chapter presents the investigated solutions to reduce the complexity and the simulation time of the tool. The two first solutions presented were to use of other kinds of games or clustering. Those solutions did not lead to positive conclusion regarding their application to the tool. The main problem is that each day is particular due to the variability of the load and generation profiles inside the IMG leading to different preferences in the ST games and to very variable cash-flows (with positive or negative peak values).

The last approach relative to MC sampling has led to better results. Among the simulations realised, the most accurate methodology is the stratified monovariate MC (for the four test cases). This methodology allows build typical days attached to a mean daily cash-flows that can be extrapolated to compute the NPV values over 20 years, according to the LT scenarios for the evolution of the load and price profiles. It allows to both reduce the number of days to simulate in a simple test case and to ensure a convergence of the cash-flows.

The monovariate stratified MC sampling without correlation (to handle a maximum of the various load and generation profiles among the available data) and using mean values inside the defined strata has therefore been chosen. The latter methodology will be integrated in a new version of the developed tool in this thesis and combined to a new formulation of the LT game and some major adjustments. All those adaptations are detailed and applied in the next chapter.

Chapter 5

Developed tool for large IMGs: adaptations and applications

This chapter presents all the considerations and adaptations that have been applied to reach a tractable tool. Remember that **the ultimate goal is to have a tool, allowing the consideration of more stakeholders and more possible actions, while decreasing the complexity and the simulation time and increasing the accuracy of the results**. For that purpose some major revisions have been applied to the first version of the tool presented in chapter 3. Some of these adjustments are relative to the methodologies and other ones are directly linked to the rules and the use of the tool. In this chapter, all those changes are explained and motivated in order to lead to a planning tool that makes sense in both its technical part and the way to consider it.

Before further developing those adaptations, some precisions have to be given regarding the utility of the tool. Indeed, the tool in its entirety allows to consider different configurations of LT investments for the stakeholders while considering a proper STEM. This tool is then a **decision support for the stakeholders** and is practically managed by the designated MGEM. Therefore, the tool can be applied in its entirety for this objective but can also, for one given configuration of investments or an already existing estate, allow a study of the profitability of those investments in the context of an IMG concept.

In the following of this chapter, the tool will be used as a decision support and therefore, lots of parameters and elements of the IMG are not fixed and must be analysed. In order to observe the IMG behaviour in different situations, the following terms are used as setting information for the different simulations:

- the *core of the tool* describes the main part of the tool that is applied for each simulation;
- the *LT configurations* are relative to each LT node of the extensive game built to simulate the tool in its entirety considering all the combinations of investments;
- the *LT scenarios* are, as already described in chapter 3, the different combinations of the LT evolutions of the load and the price profiles (Ψ_1 to Ψ_9) such as :
  - Ψ_1: Global consumption and prices remain constant;
  - Ψ_2: Global consumption remains constant and prices increase by 2% each year;

– Ψ_3: Global consumption remains constant and prices decrease by 2% each year;
– Ψ_4: Global consumption increases by 2% each year and prices are constant;
– Ψ_5: Global consumption and prices increase by 2% each year;
– Ψ_6: Global consumption increases and prices decrease by 2% each year.
– Ψ_7: Global consumption decreases by 2% each year and prices are constant;
– Ψ_8: Global consumption decreases and prices increase by 2% each year;
– Ψ_9: Global consumption and prices decrease by 2% each year.

- the *LT plans* are relative to the combination of the possible pricing applications for the IMG (regarding the fees, the exchanges between the IMG and the grid and the power cost) as well as investments plans (low or high renewable penetration);

- the *LT investigations* are relative to the different tests that can be conducted on a given state of the IMG (a LT configuration, an existing estate, a LT scenario and so on). Their are relative to the LM application, the possibility of sharing investments, the use of storage and an EVs fleet inclusion.

The core of the tool is applied for each simulation, whatever the LT considerations. The LT game, with its LT configurations, is applied for different LT plans and LT scenarios, according to the IMG and MGEM wishes. Finally, the LT investigations are realised to deeply analyse a given configuration of the IMG (depending on the previous results or for an existing estate). These principles are illustrated in Fig. 5.1.

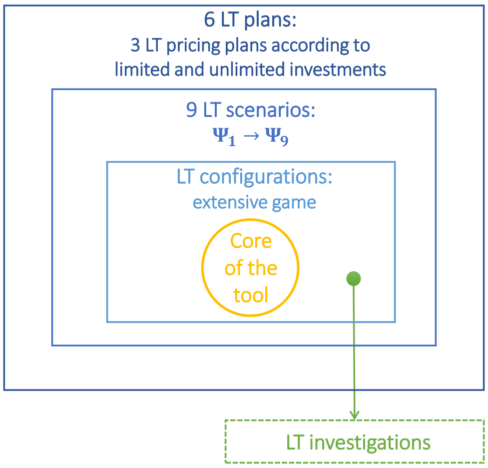


Figure 5.1 – Imbrication of the different parts of the LT tool.

Each of these settings are described in the following of this chapter. Then, a simple application on a small IMG is presented as a benchmark for the new version of the tool. Finally, all the presented principles are applied in a typical larger IMG composed of nine companies, the DSO and the IEO. Moreover, given the high number of parameters to be considered in the tool, only some of them will be investigated in more detail as they appear more relevant. They will be denoted as *key factors* and their particular impact will also be considered in a specific section of this chapter.

5.1 Core of the new tool: principle

The flowchart presented in Fig. 5.2 is the core of the new tool. The inputs of the tool are almost the same than in the first version of the tool. The only information that is more detailed regards the available area and the budget for PV and WT installations, given that maximal investments possibilities must be properly defined.

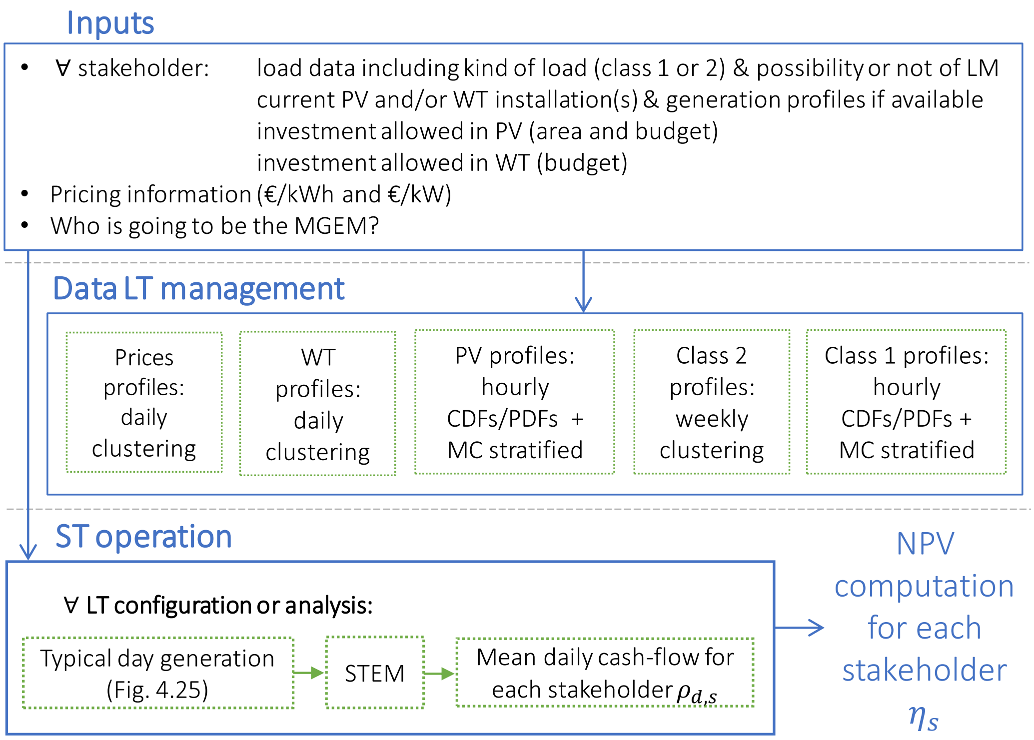


Figure 5.2 – Flowchart of the new tool dedicated to larger IMG (core of the tool).

The core of the tool has been adapted according to the new LT management of the data:

- Daily price profiles available from the spot market data are clustered with the GAK-PAM methodology. Each day, a cluster is sampled according to the occurrence of each cluster. Then, a daily profile is randomly chosen inside the cluster according to a uniform distribution, in order to have profiles as various as possible;
- This version of the tool allows to consider WT investments. Therefore, some historical WT generation profiles have to be adapted to the considered area. The normalised data are also daily clustered (with the GAK-PAM methodology) and managed exactly in the same way as price profiles;
- PV generation profiles are now concerned by the monovariate stratified MC sampling methodology previously described in chapter 4;
- The loads from class 1 can not be built by the blocks methodology anymore to be consistent with the other kinds of data. Indeed, the new methodology requests daily profiles in order to build the typical days. Therefore, the yearly profiles from class 1 are divided in weeks which are clustered (with the K-means methodology). The sampling is then performed

for a whole week according to the clusters occurrence. An uniform sampling is then performed to select a week of data inside this cluster and the concerned day inside the sampled week is used;

- The load profiles from class 2 are also now concerned by the monovariate stratified MC sampling methodology as described previously in chapter 4. Note that both the correlated and non-correlated methodologies give good results. The disadvantage of the correlated methodology is that all the data must be from the same year(s) to get realistic results. Otherwise, the non-correlated methodology should be used.

The methodology presented in chapter 4 is applied to generate the simulated days and to perform the STEM. The clustered data are sampled according to the clusters proportions, as for the price profiles. The principle applied is exactly the one presented in the previous chapter (Fig. 4.25), leading, for each day of the week d and for each stakeholder s to a mean cash-flow $\rho_{d,s}$ that can be extended to the 20 years of simulations to compute the NPV:

$$\eta_s = \sum_{y=1}^{20} \left(\frac{\sum_{d=1}^{7} 52 \times \rho_{d,s}}{(1+r)^y} \right) \tag{5.1}$$

5.2 LT configurations: new organisation of the LT extensive game

In the first version of the tool, the LT extensive game was considering the individual stakeholders as players and their respective possible decisions (regarding investment or pricing) as actions. Other games formulations have been explored but none of them seems to directly correspond to our need. Hence, the new LT game organisation will rely on a coalition game but in a derived form. Indeed, in the LT configurations, the stakeholders are gathered according to their kind of investment: PV, WT, both (PV+WT) or no investment. Therefore, they form what will be called **investment communities** that will be denoted PV_{inv}, WT_{inv}, $(PV + WT)_{inv}$ and NO_{inv}.

The LT extensive game is then built with the MGEM and those communities as players. The MGEM and the non-investors do not have decisions choices but are taken into account in the game (their cash-flows are computed by the STEM). For the investors, different quantities of investment are possible and are the actions of the game. For that purpose, the maximum investment (in kW) is defined and denoted A_{max}. It is the sum, over all concerned stakeholders of the community, of the maximal desired individual investments. These quantities are computed satisfying the peak of load of the company, its available area (in case of a PV installation) and finally its investment budget. Note that regarding the peak of load, the companies can specify if they want to invest more than their own peak and, if yes, in which proportion.

The possible actions of the LT game is then a percentage of A_{max}, denoted $a_{\%}$. This principle is illustrated in Fig. 5.3, where three quantities are considered as possible actions: a_0, a_{50} and a_{100}.

In order to compute the equilibrium, the preferences (payoffs) of each community must be known for each LT terminal node L. Those preferences are computed according to the sum of the investment cash-flows of each concerned company inside the community, $-\rho_{c,L}^{LT}$, and the

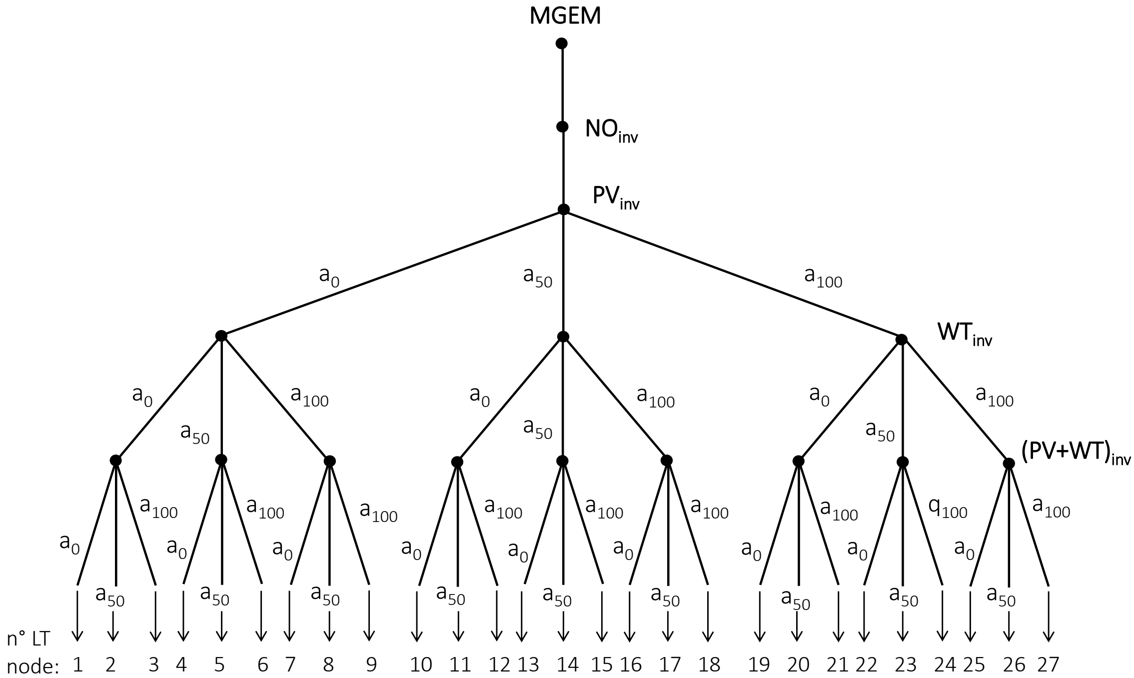


Figure 5.3 – LT game organisation in the new tool adapted for large IMGs.

extended ST cash-flows over 20 years, denoted $\eta_{c,L}$ to take into account the considered LT node L. For example, for the PV_{inv} community, its global cash-flow $\rho^{LT}_{L,PV_{inv}}$ is computed by:

$$\rho^{LT}_{PV_{inv},L} = \sum_{c \in PV_{inv}} (-\rho^{LT}_{c,L} + \eta_{c,L}) \tag{5.2}$$

The equilibrium is solved in the same way than previously presented (*cf.* chapter 2) in order to see which combination of investments (and their quantities) is the best one according to game theory framework applied to investment communities. The cash-flows for each community and for each stakeholder can then be observed.

Note that this conception of the LT game only allows to have an idea of the benefits for each stakeholder according to the different levels of investment. The equilibrium computed is valid for the community and not for each stakeholder individually. As previously mentioned, the tool can be simulated in its entirety, including this game, to be a tractable decision support for the stakeholders and only to give advices. After that, given the individual decisions of each one, the IMG can be adjusted for a given configuration and could be simulated again for this configuration ($i.e.$ for only one designated or adapted LT node).

5.3 LT scenarios inclusion regarding the extension to 20 years of the cash-flows

As previously presented, the LT evolutions of price and load profiles are uncertain and are considered through different LT scenarios. Regarding the **evolution of the prices**, as it is applied to all kinds of prices (purchasing, selling, external and internal prices), the daily equilibrium payoffs can be multiplied by the price evolution factor e_p. Only the terms linked to the GC (constant by assumption) and the maintenance cost (only linked to the initial investment cost), must be extracted from this evolution. Therefore, the daily cash-flow of each stakeholder s, $\rho_{d,s}$ must be adapted according to the e_p value each year y:

$$\rho_{d,s,y} = \rho_{d,s} \times e_p^y \tag{5.3}$$

Regarding the computation of η_s, $\rho_{d,s,y}$ now replaces $\rho_{d,s}$ in (5.1) .

Regarding the **evolution of the load profiles**, the problem is a little more complicated because the increase (or decrease) of the companies load profiles can lead to different situations, according to the generation. For example, the increase of the consumption can lead to: an increase of the quantity of electricity to buy (if the generation was already low) or the decrease of the quantity of electricity to sell (if the generation was already high) and an increase of the self-consumption rate. Inversely, the decrease of the consumption can lead to a decrease of the self-consumption and then more electricity to sell in case of generation excess and/or less electricity to buy. The consideration of the LT evolution of the load profiles is therefore difficult to take directly into account through the mean daily cash-flows.

To counter this issue, a solution could be to run the tool once for each year. However, this possibility will be too much time consuming. Therefore, instead of applying 20 times the presented methodology (once per year), it could be applied only a few times and the mean cash-flows could then be extrapolated. The initial and available load profile of each company c, denoted Λ_c, is multiplied by the load evolution factor e_l each year. It means that for each simulated year y, the initial load profile must be multiplied by e_l^y as presented in Fig. 5.4 for the five simulated years.

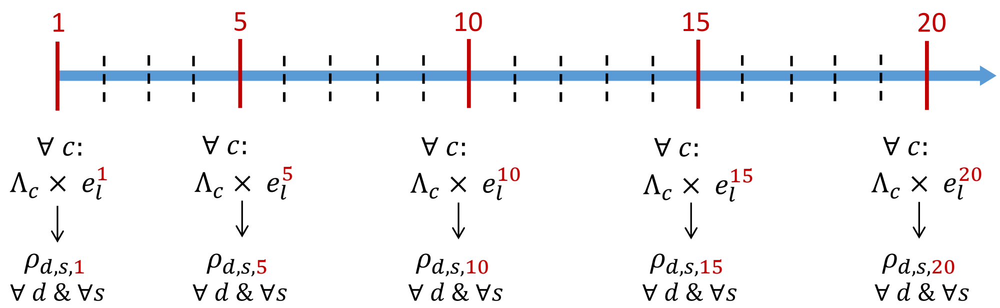


Figure 5.4 – LT evolution of principle the load profiles.

The mean daily cash-flows $\rho_{d,s,y}$ are computed for each simulated simulated year y (1, 5, 10, 15 and 20 in the example of Fig. 5.4). In order to be extended to all the 20 years of planning, the values obtained by simulations are extrapolated to each year in order to have a $\rho_{d,s,y}$ value for $y = 1, ..., 20$. Again, for the computation of η_s (5.1), $\rho_{d,s}$ is replaced by $\rho_{d,s,y}$ in order to take into account the fact that the mean cash-flows are different for each year.

The nine LT scenarios are the combination of both price and load evolutions, leading to the construction of cash-flows $\rho_{d,s,y}$ by the combination of the two above-detailed methodologies.

5.4 LT plans description

In parallel with this new formulation, the choice of *dividing to reduce the simulation time* has been done on several decisions. That means that, instead of considering more actions in the LT game which would drastically increase the simulation time and the complexity of the decision-making process (at both LT and ST time horizons), some decisions have been externalised to form *LT plans*. This will also allow to better observe and compare the results linked to different pricing and level of investment configurations.

For that purpose, the LT pricing plans have been defined according to the possible pricing policies of the new IMG regulatory framework. In the previous version of the tool, low and medium pricing were LT decisions of the MGEM. In order to put more meanings in the pricing, different LT pricing plans can be considered. The main influencing part of the flexible pricing schemes are the fees allocated to the DSO and the MGEM (for exchanges inside the IMG). Other relevant parts of the pricing are the ratio between the purchasing and the selling prices ($r_{p/s}$) and the ratio $r_{in/out}$ for the internal exchanges pricing. The peak pricing is also an important part of the electricity bill. Therefore, three LT pricing plans can be defined, crossing the combinations of lower and higher values for each relevant part of the pricing scheme and leading to some particular energy policies (see Fig. 5.5):

- **LT pricing plan 1:** neutral pricing. This first plan is quite neutral regarding the IMG and the DSO pricing parts. The used values are the same than for the benchmark (and for the first version of the tool). Those values have been inspired from the current pricing for $r_{p/s}$ and set to be as fair as possible for the DSO while promoting the IMG concept as regards the other parameters;
- **LT princing plan 2:** DSO boost pricing. This second plan promotes the DSO and the exchanges with the main grid. For that purpose, the DSO fee is increased, the difference between the grid and the IMG prices is low ($r_{in/out}$ high) and the selling price to the grid is high ($r_{s/p}$ high);
- **LT pricing plan 3:** IMG boost pricing. For this third plan, the MGEM fee is lower. The DSO fee is the same than for the first plan. In order to promote the IMG, the IMG prices are lower ($r_{in/out}$ low) and the selling price to the grid is less interesting ($r_{s/p}$ low).

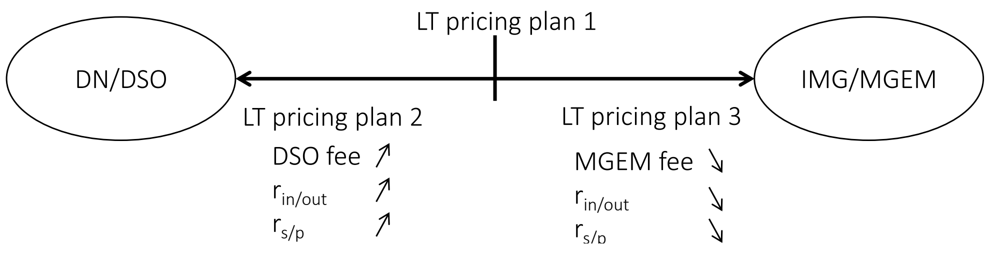


Figure 5.5 – LT pricing plans definition.

Note that those LT plans have been set to study the behaviour of the IMG with different pricing configurations representing different energy policies. All the parameters can be studied, changed and adapted according to any wished configuration by the MGEM and the IMG.

In addition to the pricing plans, different levels of investment can be considered:

- **Low RESs penetration**: the penetration of RESs is limited. The maximal investment possibilities of each company is computed by taking into account its load peak and its electricity expenses (to define its investments budget);
- **High RESs penetration**: the penetration of RESs is almost unlimited, *i.e.* the budget is almost unlimited and the power peaks of the installations can be higher than the load peaks of the companies.

Therefore, the three previously described LT pricing plans have to be simulated for both a limited and an unlimited RESs penetration. There is therefore a total of **6 LT plans**, denoted LT plan 1, LT plan 2 and LT plan 3 for limited investments and LT plan 1 unlimited, LT plan 2 unlimited and LT plan 3 unlimited for unlimited investments.

5.5 LT investigations

The LT investigations gather different tests that can be realised on one configuration of the IMG (regarding the LT configurations, the LT plans and the LT scenarios). Those tests are time consuming and/or not relevant to apply on all the simulations. This is why they are applied on selected configurations of the IMG to avoid overloading the analysis. They concern the LM applications, the possibility of sharing investments and the use of an ESS. Each one is summarised in Tab. 5.1 and is then detailed in the remaining of this section.

	Objectives	**Why is it a LT investigation?**	**How/when is it applied?**
LM (section 5.5.1)	↗ individual and IMG SCRs	Significant simulation time	LT plan 1 Ψ_1
Joint investments (section 5.5.2)	↘ investment costs	Only change the ρ_c^{LT} values	On chosen LT plans and scenarios
Associated investments (section 5.5.2)	↘ investment costs	Change of the investments principle (just for comparison)	On 1 LT plan and 1 Ψ chosen
ESS (section 5.5.3)	↗ SCRs ↘ investment costs (shared)	Significant simulation time	On 1 LT plan and 1 Ψ chosen

Table 5.1 – Summary of the LT investigations.

An additional investigation could be considered regarding the integration of an EVs fleet inside the IMG. However, the developed methodology in the context of a master thesis realised in the Electrical Power Engineering Unit of the University of Mons [132] is still incomplete and time consuming to be fully integrated and exploited in the tool developed in this thesis. For the interested reader, the intended methodology is presented in Appendix C.

5.5.1 Load management

In the first version of the tool, the LM simulation represented an important part of the execution time of the ST extensive game. Indeed, it was applied on all the simulated days over the 20 years of planning. However, it does not seem realistic to give advices to companies regarding an accurate LM application on an uncertain load profile over 20 years. Moreover, given the results of the first tool, the impact of LM does not change the undertaken LT decisions.

Therefore, in this new version of the tool, LM is not any more considered in the ST game during all the simulations (LT configurations, plans and scenarios). Indeed, the ST game is only composed of the actions of the MGEM regarding the daily trend of the IMG pricing. LM can be applied and compared only once on the typical days generated for a given plan and configuration of the IMG. Moreover, in order to be completely in line with this idea, LM is only performed for scenario Ψ_1 given that it is based on the real available data, without any uncertain evolution.

The goal of this investigation is therefore to observe, on the scenario Ψ_1, which influence LM could have for the concerned company. For that purpose, the analysis of the LM influence is based on three comparisons:

- the comparison of the mean daily cash-flows of the stakeholder s, $\rho_{d,s}$ (for each working day d), without and with LM;
- the comparison of the ST cash-flow computed over only one year ρ_s^{1y} of the stakeholder s, without and with LM;
- the comparison of the SCRs of the companies that are prosumers, without and with LM.

The assumption that this benefit could be extended to 20 years if the load profile of the company does not drastically change seems then realistic.

5.5.2 Shared investments

Until now, only individual investments were considered for the stakeholders. Inside such an IMG, it makes sense that shared investments can be considered in order to reduce the investments costs as well as the maintenance and operation costs. Indeed, we can consider an installation cost ($€/kW$ installed) that decreases when the total installed power increases. Therefore, if an unique RES investment is consider for all companies, the overall investment cost should be reduced compared with the sum of the individual investment costs.

The shared installation is therefore unique for the IMG but it is spread between each company c according to its participation $RES_{\%,c}$ in the RES installation. This participation can be quantified according to two investment visions:

- The first vision is the **joint investment**. The sizing of the installation is done as previously defined, $i.e.$ according to the load peak and the budget of each company individually, and then, the defined installations are gathered as a joint purchase. The only change concerns the LT cash-flow of investments of the companies c (ρ_c^{LT});

- The second vision is **associated investments**, which means that the MGEM performs an optimised shared investment for the companies taken as a whole according to the load peak of the IMG and the type of load profile (class 1 or 2):
  - WT is promoted for companies of class 1 as they have higher base-load profiles with a shape independent of night and day. PV is promoted for companies of class 2, given their daily bell curves;
  - If a company already has a PV installation, a new WT installation will be promoted, and vice versa, to avoid oversizing the same type of investment;
  - The sizing of global PV and WT installations takes into account the sum of the load peak of the concerned companies. The costs are divided between the companies according to the weight of their respective peak over the overall peak (W_c for a company c) for the concerned installation.

  This second vision changes somehow the perspective of the tool because the stakeholders are not anymore keeping the full control on their investments possibilities. The kind and the amount of investments (that are, in this case, decided by the MGEM) are therefore changed compared to the individual investments.

Regarding the STEM, for both visions, the principle set up in the tool remains unchanged if losses are neglected. That means that each company can in priority self-consume his part of the generation. If there is a surplus, it is sold to the IMG (or the grid) and if there is a lack, it is bought to the IMG (or the grid), whatever the installation is individual or shared.

5.5.3 Energy storage systems

The next investigation concerns the installation of an ESS to increase the self-consumption of the IMG. The first version of the tool showed that such ESS is too expensive to be profitable for the companies. Therefore, in this version of the tool, the ESS investment is only considered as a shared investment. The capacity size of the ESS is computed according to the peak of the installed RESs. The participation of each company c ($ESS_{\%,c}$) is proportional to his peak of installed RES(s) ($RES_{\%,c}$), itself depending on his peak of consumption as already explained.

The consideration of storage in this tool is quite simple in order to just give the stakeholders an idea of the benefits it could possibly yield. Therefore, if a shared ESS is installed in the IMG, the goal would be to self-consume a maximum of the internal generation and to decrease the exchanges with the main grid. Indeed, the electricity that can be stored is the generation surplus after all the internal exchanges. The discharged electricity is used in case of a lack of electricity inside the IMG, before purchasing to the main grid. As the goal is to minimise those values, that can be also formulated as maximising the quantities to charge and to discharge in the ESS.

According to the notations used in the chapter 2 of this thesis, after the IMG operation, the generation surplus that could be sold to the main grid $q_{sale,s,h}$ and the lack of energy that could be purchased to the main grid $q_{purch,s,h}$ can be respectively computed by (5.4) and (5.5) for each company c and hour h.

$$q_{sale,c,h} = g_{c,h} - Z_{c,h} \tag{5.4}$$

$$q_{purch,c,h} = \lambda_{c,h} - X_{c,h} \tag{5.5}$$

The optimisation inputs and outputs for each hour h of each day is presented in Fig. 5.6. At each hour h, the global quantity of energy that can be charged $Q_{ch,h}$ or discharged $Q_{dis,h}$ is maximised and computed according to the following assumptions:

- The amount of electricity that can be charged (or discharged) depends on the power of charge $P_{ess,ch}$ (or power of discharge $P_{ess,dis}$) of the battery. This amount is maximised for each hour. That means that the batteries are always used as much as possible in order to reach their maximum benefit. An efficiency factor eff is also taken into account for both the charge and discharge modes;
- The battery is described by its SOC at the beginning of the day ($h = 1$) $SOC_{ess,1}$ and the one at the end of the day ($h = 24$) $SOC_{ess,24}$. The minimum and maximum SOC limits ($SOC_{ess,min}$ and $SOC_{ess,max}$) need to be specified as inputs of the tool in the batteries characteristics. For the simulated Mondays, the $SOC_{ess,1}$ are uniformly sampled between its limits. For the other days, the $SOC_{ess,1}$ are sampled among the available $SOC_{ess,24}$ of the previous day (as the number of values for each day can be different and the tool is only pseudo-sequential);
- Given the organisation of the tool, the ageing of the batteries is difficult to take into account. Therefore, it will be neglected, again in the optic of considering the system in its full and perfect operation.

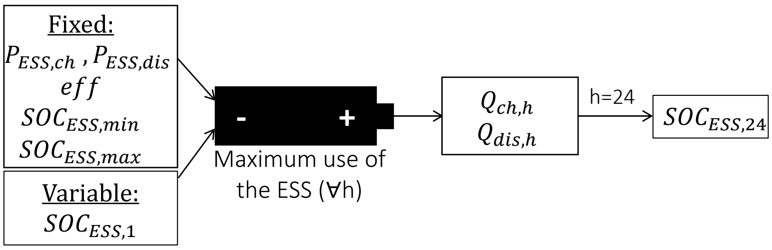


Figure 5.6 – Inputs and outputs summary for the daily use of ESS.

The amount of energy that can be charged $q_{ch,h,c}$ or discharged $q_{dis,h,c}$ by each company c needs then to be defined according to his part in the ESS ($ESS_{\%,c}$):

$$q_{ch,h,c} = ESS_{\%,c} \times Q_{ch,h} \tag{5.6}$$

$$q_{dis,h,c} = ESS_{\%,c} \times Q_{dis,h} \tag{5.7}$$

In the charging mode: if $q_{ch,h,c} > q_{sale,c,h}$, the whole surplus quantity $q_{sale,c,h}$ can be stored and the new quantity of energy that has to be sold to the main grid $q_{sale,c,h}$ is equal to 0. Otherwise, only the quantity of energy $q_{ch,h,c}$ can be charged and the remaining energy $q_{sale,c,h} - q_{ch,h,c}$ is the new quantity that must be sold to the main grid.

In the discharging mode: if $q_{dis,h,c} > q_{purch,c,h}$, the whole lack of energy $q_{purch,c,h}$ can be discharged and the new quantity of energy that has to be purchased to the main grid $q_{purch,c,h}$ is equal to 0. Otherwise, only the quantity of energy $q_{dis,h,c}$ can be discharged and the remaining part of energy $q_{purch,c,h} - q_{dis,h,c}$ is the new quantity that must be purchased to the main grid.

At each hour h, the state of charge of the battery $SOC_{ess,h}$ is adapted according to these values.

This consideration of ESS allows a new kind of exchanges inside the IMG. After these steps, the daily cash-flows are computed for every companies with the new quantities of energy that can be purchased or sold to the main grid and the remaining of the simulation is kept unchanged. **Given that this process is time consuming, it should be applied on a desired configuration of the IMG in order to evaluate if, over the** 20 **years of planning and given the investment cost of the ESS, it is interesting or not for the companies (assuming an ideal use of the ESS).**

5.6 Simple application to a small IMG: benchmark

The tool is run a first time to benchmark the different adaptations thought to the previous version of the tool. For that purpose, the considered IMG is the same as in chapter 3 (Fig. 3.11) and composed of 3 companies ($C = 3$): 2 consumers (1 and 2) and 1 prosumer (3). So, there is 4 stakeholders: the DSO as MGEM and the three companies. This IMG is connected to the 10.5 kV DN. Companies 1 and 3 are considered as companies from Class 2 ($C_2 = 2$) while the company 2 belongs to Class 1 ($C_1 = 1$).

In chapter 3, regarding the LT decisions, the consumers 1 and 2 could either invest in a PV installation (PV) or do nothing (No). The prosumer (c=3) could choose to invest in an ESS or to do nothing (No). In this new simulation, storage is not considered but, as WT can be added, we will consider that the prosumer 3 could invest in a WT installation (it is part of the WT community). The consumer 2 could invest in both PV and WT installations (it is part of the PV+WT community). The first consumer, given the trend of its load profile, could just invest in a PV installation (it is part of the PV community). Regarding the management of the data, as the available data are not all synchronous, the non-correlated monovariate MC sampling methodology is used.

The tool is run for the first scenario Ψ_1 considering no evolution of the price and load profiles over the 20 years of planning. Regarding the IMG pricing, it is the same than for the medium prices actions of the MGEM in the first version. For one scenario, the simulation time was about 92 minutes with the first version. With this version, the simulation time of Ψ_1 is about 14 minutes, which already shows a first advantage of the new tool.

Regarding the obtained NPVs after 20 years, the ones without any investments (LT node 1 in Fig. 5.3) can be compared in order to give an idea of the similarity of the results: for the companies 1 and 3 the difference between the results obtained with the first and the second version of the tool is less than 3%. Given the fact that the convergence is checked in the second version of the tool, the values are more reliable with the latter. However, the accuracy of the first version of the tool was not so bad. For the company 2, as she is a huge industrial company (from class 1), her NPV differs of about 12%. Indeed, given the irregularity of such a load profile, the NPV can be different from a simulation to another with the first version of the tool. Again, the new version of the tool ensures that the payoff value converges. However, the results are less stable for such a kind of company than the ones from class 2. Note that the NPV of the MGEM depends on the ones of the companies and is therefore affected by the variability of the company 2.

Tab. 5.2 gathers the number of simulations I_d for each day d. The sum is equal to 3037, which means that the number of simulated days is divided by more than 2.4 compared to the first version of tool where $365 \times 24 = 7300$ days were simulated.

d	1	2	3	4	5	6	7
$I_{simu,d}$	419	315	408	371	386	675	463

Table 5.2 – Number of simulated days.

The equilibrium obtained with the first version of the tool was to invest in PV installations of $180kWp$ and $400kWp$ for companies 1 and 2 respectively, and to do nothing for the third company. In this second simulation, the maximum budget of each company has been arbitrarily set to 200000, 500000 and 300000 €, based on their electricity bill. With the possibility of investing in a WT installation, the equilibrium is now different:

- For company 1: invest in a PV installation of $167kWp$;
- For company 2: invest in a PV installation of $68kWp$ and a WT installation of $204kWp$;
- For company 3: invest in a WT installation of $145kWp$.

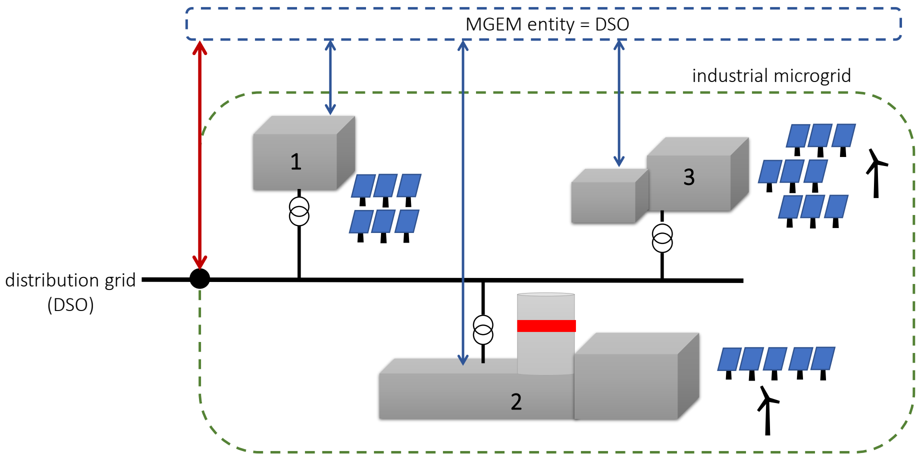


Figure 5.7 – Chosen investments of the studied IMG.

Those investments allows the benefits presented in Tab. 5.3. As the MGEM cash-flow is positive, that means that a gain of 12% is reached. For the companies, as their cash-flows are negative, it means that they realise savings. The benefit of the WT installations is clearly demonstrated given the important savings for companies 2 and 3.

s	Ψ_1
MGEM	$+12\%$
c=1	-18%
c=2	-26%
c=3	-79%

Table 5.3 – Gains/losses analysis for scenario Ψ_1.

Finally, as DLM was considered for each day for the companies 1 and 3 in the first version of the tool, it seems interesting to compare its benefit computed with the first version to the ones computed with the new one. DLM is therefore applied on the LT equilibrium node. Remember that with the first version of the tool, the LM application was allowing only the prosumer 3 to make some savings and was not really effective for the company 1.

The new consideration of LM, applied to the equilibrium node only, should therefore lead to similar results. For that purpose, the direct cash-flow without and with LM has been computed over 1 year for each stakeholder in the configuration obtained at the LT equilibrium. These cash-flows only take into account the inputs and outputs linked to the STEM. They are gathered in Tab. 5.4. Their values confirm the previous observations: the LM application is attractive for the third company (s=4). Given that less energy is exchanged inside the IMG with LM, the MGEM ($s = 1$) cash-flow is decreased. For the companies 1 (s=2) and 2 (s=3), LM practically does not affect their cash-flows. That means that performing DLM is not effective for the first company, as found with the initial version of the tool.

s	Without LM [€]	With LM [€]
ρ_1^{1y}	+64823	+61817
ρ_2^{1y}	-50135	-49318
ρ_3^{1y}	-93560	-94145
ρ_4^{1y}	+17132	+20663

Table 5.4 – Comparison of the cash-flows over 1 year without and with LM.

5.7 Application to a larger IMG of nine companies with the DSO as MGEM

A more realistic IMG, composed of 9 companies with various load profiles is considered as a test case for a global study with the developed planning tool. This larger IMG is presented in Fig. 5.8.

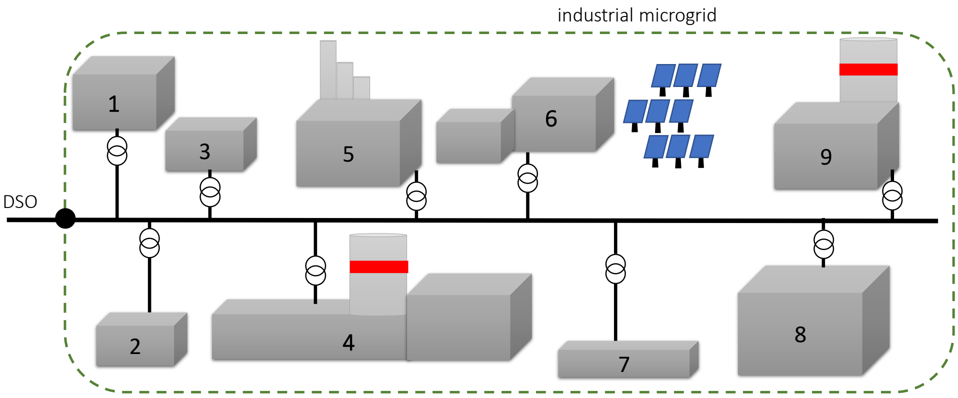


Figure 5.8 – Representation of the larger IMG.

In the following of this section, the inputs of the IMG are first presented in detail. Then, the 6 LT plans are simulated and the adaptable parameters relative to them are specified. For each one, the 9 scenarios (Ψ_1 to Ψ_9) are applied in order to see their influence on the results. The results of the performed simulations are depicted in 6 tables:

- The first one shows the equilibrium and the total number of iterations for each scenario;
- The second one shows the percentages of gains or losses for each company compared with the simulated case without IMG. This percentage is computed by:

$$\%\eta_s = \frac{(\eta_s - \eta_{0,s})}{\eta_{0,s}} \tag{5.8}$$

- The third table shows the occurrence of each kind of daily IMG pricing;
- The fourth table shows the metrics for the internal exchanges (TIC, REP, IEP) as already presented in chapter 3;
- The fifth table shows the metrics for the external exchanges (PP and SP) as also presented in chapter 3;
- The sixth table shows the self-consumption rate of each company.

The LT investigations are then performed for a (some) chosen LT plan(s) and scenario(s).

Note that the tool could be run for a huge number of combinations of all the parameters and for all kinds of company profiles. The following analysis is based on a single IMG example. The LT plans are all simulated according to all the scenarios and then, different LT investigations and analysis are performed. However, their number will be limited in order to be relevant and as clear as possible to expose and to understand.

5.7.1 LT plans simulations with limited investments

Objective: run the entire tool for the 3 LT pricing plans with limited investments (LT plan 1, LT plan 2 and LT plan 3) according to the 9 scenarios (Ψ_1 to Ψ_9).

The results shown in this section can be considered in two ways. Firstly, each LT plan can be analysed individually in order to compare the nine simulated scenarios. Secondly, the LT plans can be considered as a whole in order to compare and to see the influence of the different pricing considerations on the IMG behaviour. As previously mentioned, some *key factors* will progressively be defined in the following analysis. Those factors will be deeply detailed and analysed in the next section.

Tab. 5.5 gathers the main characteristics of each company. All the companies have been attributed to a class, which defines the way to manage in a long-term perspective the load data. Each company must then specify if she already has a PV or a WT installation (columns $PV_{current}$ and $WT_{current}$) and if she desires to invest in a new PV and/or WT installation (columns PV_{invest} and WT_{invest}. Each company has to provide at least one year of load profile and, potentially, one year of generation profile if she is a prosumer.

Regarding the possible investments, a maximal budget must be specified in the next columns (in $k€$). For the following simulations, this budget is set for each company in respect with the projected electricity expenses over the 20 years of planning. Those values have been arbitrarily chosen to observe the behaviour of the tool with realistic budget values for this first complete analysis. The same reasoning has been done regarding the available area (in m^2). The last columns r_{peak} allows the company to inform if she just wants to cover her peak ($r_{peak} = 1$) or if she wants to give additional services by over-sizing its installation ($r_{peak} > 1$). For this LT plans, this value is set to 1 for all the companies in order to observe the IMG in its fundamental concept.

s	Class	$PV_{current}$	$WT_{current}$	PV_{invest}	WT_{invest}	Budget [k€]	Area [m^2]	r_{peak}
c=1	2	no	no	yes	no	600	10000	1
c=2	2	no	no	yes	yes	900	50000	1
c=3	2	no	no	yes	no	300	10000	1
c=4	1	no	no	yes	yes	5000	100000	1
c=5	2	no	no	yes	no	800	50000	1
c=6	2	yes	no	no	yes	300	10000	1
c=7	2	no	no	yes	no	900	100000	1
c=8	2	no	no	yes	yes	850	20000	1
c=9	1	no	no	no	yes	3000	50000	1

Table 5.5 – Inputs of the tool.

Regarding the LT pricing plans, the parameters are specified in Tab. 5.6. r_{in}^{fee} and r_{in}^{dso} are used to quantify the internal fees of the MGEM and the DSO, respectively (from a percentage of the internal commodity price).

Remind that, the first one is a medium plan. $r_{p/s}$ and the amount of the fees are inspired from the existing pricing. In the second LT plan, the pricing parameters are adapted in order to decrease the difference between the internal and external prices, to increase the selling price of electricity and the fees of the DSO. This plan is therefore a priori established in order to reach interest for the DSO. The third plan is established with the opposite idea. That means that the IMG is promoted thanks to very attractive internal prices (lower $r_{in/out}$). The selling price is less interesting (which is, partly, unfavourable for the DSO). The DSO fee is the same as for the first LT plan while the MGEM fee is decreased (which should be interesting for the IMG companies).

	r_P	$r_{in/out}$	$r_{p/s}$	r_{in}^{fee}	r_{in}^{dso}
LT plan 1	0.10	0.90	0.78	0.15	0.15
LT plan 2	0.10	0.95	0.90	0.15	0.25
LT plan 3	0.10	0.70	0.60	0.05	0.15

Table 5.6 – LT plans variable pricing parameters.

Tab. 5.7 gathers the generated maximum values of the PV and/or WT installation(s) ($PV_{invest,max}$ and $WT_{invest,max}$, respectively) for each company, as well as the corresponding LT cash-flow (ρ_c^{LT}) attached for each one. The PV and WT costs used are shown in Fig. B.1a and B.1b, respectively in the Appendix B. The decrease of the these prices has been established to be relevant while realistic to our knowledge. Other values could be tested in order to see the impact on the LT cash-flows and therefore, on the LT decisions of investments.

s	l_c^{peak} [kW]	$PV_{invest,max}$ [kW]	$WT_{invest,max}$ [kW]	ρ_c^{LT} max [k€]
c=1	206	206	0	264
c=2	211	158	53	313
c=3	106	106	0	136.5
c=4	2095	419	1676	3091.5
c=5	212	212	0	271.8
c=6	324	0	145	300.5
c=7	211	211	0	270.5
c=8	418	281	69	500.8
c=9	1096	0	1096	1722.9

Table 5.7 – Maximum long-term investments information.

The considered IMG is characterised by a maximum load peak ($l_{IMG}^{peak} = \sum_c l_c^{peak}$ of about 4879 kW. Regarding the other columns, the presented values are the maximum investment possibility for each company. According to the equilibrium LT node (see Fig. 5.3), the investments will be there maximum values (a_{100}), the half of these values (a_{50}) or zero (a_0).

Regarding the ST game, as previously described, 4 daily pricing decisions are available for the MGEM: the first case corresponds to the same trend than external price, the second one is a constant price (equal to the average of the external price), the third one is generated with an opposite trend than the external price and the fourth one is inversely proportional to the amount of generation available inside the IMG.

LT plan 1 with limited investments

In Tab. 5.8, we can observe that, given the input values, all the scenarios lead to the advice of installing 100% of the possibility of investments, *i.e.* the **equilibrium** (denoted Eq. in the tables) is the LT node 27 of the LT game shown in Fig. 5.3.

Regarding the **number of simulated days** ($\sum I_{simu,d}$), it is higher than for the LT node 1 (as previously shown for the small IMG). Indeed, given the amount of additional elements to take into account, the number of iterations to reach the convergence is increased. For each simulation, if we look at the number of iterations from LT node 1 (no investments) to LT node 27 (with all investments), this value increases progressively. Note that, for scenarios Ψ_4 to Ψ_9, this number is in fact approximately multiplied by 5 given that the tool has been run 5 times (for years 1, 6, 11, 16 and 20) compared to the scenarios Ψ_1, Ψ_2 and Ψ_3.

Regarding Tab. 5.9, **the percentages of gains or losses** of the MGEM (=DSO) are relatively close to 0. He is only making small losses with scenarios Ψ_2 and Ψ_5. Otherwise, his benefits vary between 0 and 10%. That means that with this LT pricing, the IMG does not have a negative impact for the DSO and offsets the losses that could be linked to the decrease of the exchanges with the distribution network.

Regarding the companies, they are all making important savings thanks to the investments and the IMG operation. For the majority of the companies, the maximum gains occur with scenario Ψ_8, *i.e.* when the electricity prices increase and the loads decrease.

Regarding **the daily pricing** applied inside the IMG, Tab. 5.10 shows that the main choice is the second case, *i.e.* to apply a constant price inside the IMG. The second choice is to apply a daily pricing that follows the same trend as the grid pricing (case 1). Finally, the third case (with an opposite trend respect to the grid pricing) is chosen only about 6% of the time, while the last trend is almost never chosen.

Among **the internal metrics** gathered in Tab. 5.11, the renewable penetration (REP) and internal exchanges probability (IEP) properly follow the evolution of the load profiles: when the load increases (Ψ_4, Ψ_5 and Ψ_6), the REP is lower and the proportion of internal exchanges decrease. When the load decreases (Ψ_7, Ψ_8 and Ψ_9), the REP is higher and the proportion of internal exchanges increases. For **the exchanges with the main grid**, the PP value is slightly increased when the load increases ((Ψ_4, Ψ_5 and Ψ_6) and slightly decreased when the load decreases (Ψ_7, Ψ_8 and Ψ_9) compared to scenarios Ψ_1, Ψ_2 and Ψ_3 (see Tab. 5.12).

In Tab. 5.13, **the self-consumption rates** are supposed to be the same for the identical load evolutions (Ψ_1 to Ψ_3, Ψ_4 to Ψ_6 and Ψ_7 to Ψ_9). This assumption is confirmed with a maximum variation of about 5%. That means that the MC stratified sampling set up for the load profiles of class 2 and the PV generation, as well as the clustering for the WT generation, the prices and the loads of class 1, converge to similar values for each simulation, which can partly testify to the robustness of the developed tool.

LT plan 2 with limited investments

Again, as presented in Tab. 5.14, the LT decision is always to invest 100% of the companies possibilities. The number of iterations follows the same trend that for the first plan.

Regarding the gains and losses of Tab. 5.15, their values seem, at first glance, quite confusing regarding the values of the previous plans. Indeed, the losses or the gains of the MGEM are quite similar to the ones presented in the first plan. This can be explained by looking to the Tab. 5.16, regarding **the daily prices inside the IMG**. Indeed, the proportion of each price case is changed compared to the first plan. In this second plan, the first and the second cases are almost equally chosen and in the large majority of the time.

This change can be explained by looking at the Fig. 5.9, gathering different price cases for the LT plans. The price case 1 is globally higher for the second plan (blue curve) than in the first plan (green curve) (because $r_{in/out}$, $r_{p/s}$ and the DSO fee are higher). The constant price (orange curve), computed from the external price, is the same for both LT plans. Therefore, the following observations can be realised **to compare LT plan 1 and 2**:

- **LT plan 1**: constant price is always more interesting for the DSO (MGEM) then price case 1. Given that the pricing is not really interesting for the DSO (lower green curve), constant prices are often chosen in order to be fairer with the DSO;

- **LT plan 2**: the first price case is higher and therefore, constant price is less chosen in order to be fairer with the companies, *i.e.* to mitigate the gain of the DSO and the decreases of the losses of the companies linked to the change of pricing level.

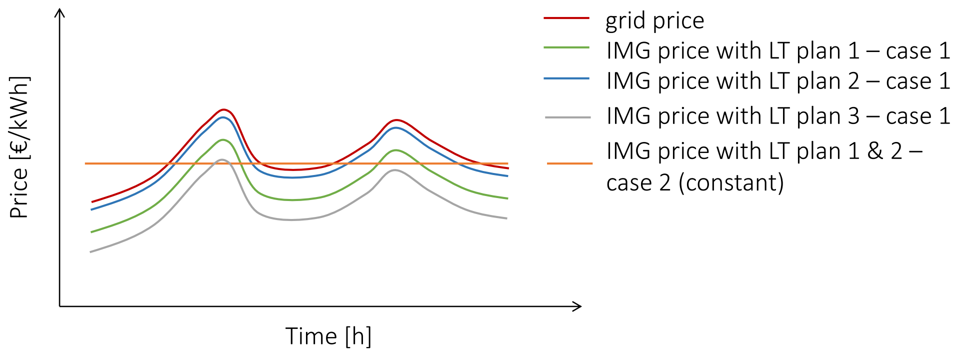


Figure 5.9 – Illustration of price cases for LT plans 1, 2 and 3.

As a result of these observations, the gain or loss of each stakeholder are in the same order of magnitude than for the first LT plan, which reflects the proper role of game theory at the ST time horizon to obtain fair cash-flows for each one.

All the other parameters (internal metrics in Tab.5.17, external metrics in Tab.5.18 and self-consumption rates in Tab.5.19) are quite similar and with the same trend than for the first LT plan.

LT plan 3 with limited investments

Once more, all the scenarios lead to 100% of investments, as shown in Tab. 5.20. The number of iterations also keeps the same trend.

The analysis of Tab. 5.21 and 5.22 confirm the previous observations made for LT plan 2. Indeed, this time, the constant price is almost always chosen by the tool. This is in accordance with the Fig. 5.9, on which the price case 1 for LT plan 3 is the grey curve and is lower than all the previous variable curves. The choice of the constant price seems therefore appropriate to be as fair as possible with the DSO/MGEM even if, globally, his losses are increased of several percent with this LT plan.

The value of this constant price should be changed in order to see its influence on the 3 LT plans analysis. It can be considered as a *key factor* of the tool to be further analysed.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
Eq.	27	27	27	27	27	27	27	27	27
$\sum I_{simu,d}$	17309	18778	18045	102255	90104	90710	79622	91911	91440

Table 5.8 – LT plan 1 - Equilibrium and number of simulated days analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
MGEM	+0.22	-1.90	+0.84	+10.5	-1.38	+0.65	+2.64	+9.14	+1.97
c=1	-25.3	-27.1	-22.2	-23.4	-24.9	-22.1	-30.1	-31.9	-28.1
c=2	-29.2	-29.6	-27.9	-26.1	-25.9	-25.7	-34.4	-35.4	-33.9
c=3	-27.8	-29.3	-24.8	-26.7	-27.6	-24.9	-31.9	-34.0	-29.9
c=4	-66.6	-64.2	-68.1	-65.0	-66.9	-67.7	-64.4	-55.4	-66.8
c=5	-21.3	-22.8	-19.0	-19.8	-20.6	-18.6	-24.8	-26.3	-23.4
c=6	-91.9	-78.2	-106	-68.9	-60.3	-78.6	-133	-114	-163
c=7	-19.3	-20.8	-17.0	-17.8	-18.4	-16.7	-22.5	-23.9	-21.2
c=8	-37.5	-39.1	-33.8	-34.7	-36.0	-33.1	-45.0	-48.1	-42.1
c=9	-67.4	-84.0	-74.0	-63.4	-66.5	-78.4	-70.4	-61.7	-74.0

Table 5.9 – LT plan 1 - Gains/losses analysis for each scenario [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
1	19.97	19.15	19.38	20.26	20.28	20.82	19.40	19.57	19.46
2	73.94	74.29	74.18	73.05	72.58	72.24	74.75	74.53	74.74
3	6.05	6.49	6.41	6.67	7.13	6.93	5.76	5.82	5.71
4	0.03	0.07	0.03	0.02	0.01	0.01	0.09	0.08	0.09

Table 5.10 – LT plan 1 - Daily pricing percentages [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
TIC [kW]	4699	4699	4699	4699	4699	4699	4699	4699	4699
REP [%]	49.59	54.11	49.75	46.83	46.44	45.01	53.97	52.82	52.32
IEP [%]	69.21	69.56	68.50	66.66	65.06	64.97	72.33	72.1	71.81

Table 5.11 – LT plan 1 - Internal exchanges analysis.

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
PP [%]	84.69	81.93	84.37	86.57	87.02	87.91	81.48	82.02	82.55
SP [%]	15.31	18.07	15.63	9.67	12.98	12.09	18.52	17.98	17.45

Table 5.12 – LT plan 1 - External exchanges analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
c=1	61.09	57.64	62.77	58.34	63.85	61.42	57.59	60.83	58.33
c=2	96.47	97.05	96.32	98.60	98.21	98.39	92.59	91.81	93.29
c=3	61.22	58.19	62.96	60.29	65.34	63.48	56.06	58.67	56.22
c=4	77.91	79.31	78.39	82.68	82.08	83.79	79.30	79.15	79.45
c=5	82.44	81.071	83.41	84.13	87.26	86.07	75.65	77.69	75.73
c=6	66.34	68.89	65.75	74.39	72.89	73.39	58.29	56.58	59.96
c=7	77.02	70.94	78.86	72.30	78.26	75.84	73.52	76.35	73.95
c=8	52.56	49.53	54.62	48.72	54.60	52.38	49.86	53.13	51.20
c=9	74.38	65.89	72.56	71.56	73.21	74.22	68.99	70.35	70.88

Table 5.13 – LT plan 1 - Self-consumption rates [%].

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
Eq.	27	27	27	27	27	27	27	27	27
$\sum I_{simu,d}$	16584	11653	26831	94325	96717	82248	81123	94310	84436

Table 5.14 – LT plan 2 - Equilibrium and number of simulated days analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
MGEM	-0.91	+1.95	+1.55	+4.98	-7.25	+6.40	-0.97	-0.04	-2.26
c=1	-25.7	-26.5	-23.2	-22.5	-24.0	-21.5	-29.5	-31.6	-27.9
c=2	-28.4	-29.0	-28.2	-25.3	-25.2	-25.3	-34.0	-34.0	-33.8
c=3	-27.1	-28.9	-25.0	-25.6	-27.0	-24.4	-31.5	-33.8	-29.8
c=4	-66.7	-56.3	-70.7	-68.8	-70.6	-71.4	-66.1	-57.2	-68.2
c=5	-20.7	-21.9	-19.3	-18.7	-19.7	-17.8	-24.0	-25.8	-22.9
c=6	-91.4	-79.4	-108	-68.5	-59.8	-79.9	-136	-115.4	-169
c=7	-18.5	-19.6	-17.2	-16.7	-17.7	-15.8	-21.4	-23.2	-20.5
c=8	-38.0	-39.6	-35.0	-34.6	-35.9	-33.5	-45.2	-48.4	-42.8
c=9	-76.4	-86.7	-73.6	-70.8	-76.5	-75.7	-69.7	-75.9	-89.1

Table 5.15 – LT plan 2 - Gains/losses analysis for each scenario [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
1	42.01	39.06	41.74	41.73	40.78	41.47	41.43	41.05	40.86
2	43.01	46.38	43.53	42.95	43.37	42.65	44.17	44.63	44.76
3	14.95	14.54	14.71	15.31	15.84	15.87	14.36	14.26	14.34
4	0.03	0.02	0.02	0.01	0.01	0.01	0.04	0.06	0.04

Table 5.16 – LT plan 2 - Daily pricing percentages [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
TIC [kW]	4699	4699	4699	4699	4699	4699	4699	4699	4699
REP [%]	50.41	51.02	48.94	46.51	46.11	46.04	50.90	52.43	54.09
IEP [%]	68.64	70.93	68.27	65.77	64.83	65.04	71.51	71.77	72.12

Table 5.17 – LT plan 2 -Internal exchanges analysis.

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
PP [%]	84.90	84.03	84.89	86.79	86.79	87.19	83.74	82.33	81.54
SP [%]	15.10	15.97	15.11	13.21	13.21	12.81	16.26	17.67	18.46

Table 5.18 – LT plan 2 -External exchanges analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
c=1	56.93	58.64	61.31	60.73	63.96	62.77	60.32	59.83	60.64
c=2	96.90	96.55	97.13	98.4	98.47	98.28	92.68	92.28	91.54
c=3	57.62	58.85	61.55	62.5	65.35	64.47	58.38	57.65	58.64
c=4	82.93	82.73	77.96	80.80	81.48	82.73	81.39	79.72	79.12
c=5	80.42	81.12	82.56	85.80	87.20	86.58	77.58	76.76	77.60
c=6	67.83	67.00	68.78	73.84	74.11	73.16	58.27	58.04	55.77
c=7	71.82	73.79	77.40	74.33	78.07	76.83	76.32	75.46	76.34
c=8	48.08	49.92	53.52	50.99	55.18	53.36	52.71	52.57	53.08
c=9	73.89	62.58	75.80	74.72	71.96	72.97	72.59	70.68	70.19

Table 5.19 – LT plan 2 - Self-consumption rates [%].

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
Eq.	27	27	27	27	27	27	27	27	27
$\sum I_{simu,d}$	15530	20418	17680	99684	78624	86972	97126	98506	87884

Table 5.20 – LT plan 3 - Equilibrium and number of simulated days analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
MGEM	-6.68	-3.92	-3.74	-3.26	+2.33	-3.23	+0.01	-6.22	-11.8
c=1	-26.9	-26.6	-24.0	-24.4	-25.6	-22.6	-31.1	-33.0	-29.1
c=2	-30.5	-29.9	-28.8	-26.8	-26.8	-26.3	-35.4	-35.5	-34.3
c=3	-28.7	-29.5	-26.1	-27.4	-28.7	-25.9	-33.4	-35.0	-31.1
c=4	-66.5	-61.3	-62.5	-66.2	-59.7	-66.8	-63.7	-63.2	-69.6
c=5	-22.7	-22.6	-20.0	-20.5	-21.3	-19.4	-26.0	-63.2	-24.4
c=6	-91.9	-80.5	-108	-69.2	-61.5	-80.5	-134	-113	-159
c=7	-21.0	-20.7	-18.8	-18.8	-19.5	-17.8	-23.8	-24.7	-22.5
c=8	-37.5	-39.6	-34.9	-35.3	-36.5	-33.9	-46.2	-48.4	-42.1
c=9	-92.3	-93.1	-81.4	-75.5	-70.3	-64.8	-70.5	-66.0	-89.8

Table 5.21 – LT plan 3 - Gains/losses analysis for each scenario [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
1	0.26	0.33	0.22	0.29	0.32	0.32	0.23	0.24	0.23
2	99.38	99.33	99.54	99.36	99.37	99.35	99.44	99.39	99.43
3	0.32	0.30	0.24	0.33	0.29	0.31	0.24	0.26	0.26
4	0.04	0.04	0.24	0.02	0.02	0.02	0.09	0.11	0.08

Table 5.22 – LT plan 3 - Daily pricing percentages [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
TIC [kW]	4699	4699	4699	4699	4699	4699	4699	4699	4699
REP [%]	53.26	48.51	47.04	46.12	47.4	44.74	53.34	53.27	53.74
IEP [%]	68.63	69.18	68.11	65.52	65.97	64.43	72.11	71.88	72.17

Table 5.23 – LT plan 3 - Internal exchanges analysis.

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
PP [%]	82.42	85.49	86.19	86.96	86.13	87.92	82.03	82.25	81.58
SP [%]	17.58	14.51	13.81	13.04	13.87	12.08	17.97	17.75	18.42

Table 5.24 – LT plan 3 - External exchanges analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
c=1	62.94	60.19	59.28	62.13	61.73	61.46	58.48	56.98	60.14
c=2	96.75	96.77	97.32	98.42	98.26	98.62	92.05	93.36	91.79
c=3	62.74	60.84	59.48	63.68	63.62	63.21	56.64	55.44	57.99
c=4	80.22	82.12	83.71	81.09	81.24	84.36	79.50	78.49	78.58
c=5	83.46	82.19	81.46	86.52	86.01	86.53	76.04	75.44	77.01
c=6	67.50	66.76	69.03	74.37	72.95	75.14	57.24	59.81	56.50
c=7	78.00	76.61	75.02	75.19	75.86	75.04	74.48	72.20	75.85
c=8	54.51	52.26	50.37	52.95	53.12	51.96	50.58	49.53	52.69
c=9	63.33	72.21	72.84	72.97	70.70	73.12	71.78	73.66	69.30

Table 5.25 – LT plan 3 - Self-consumption rates [%].

Time of return on investments analysis

In order to further analyse the obtained results, the time of return on investment(s) of the companies can be evaluated. For that purpose, the $ROI_{\mu g,c}$ of each company c is computed by incrementing the investment cash-flow ρ_c^{LT} by the difference between $\rho_{c,y}^{ST}$ and the equivalent cash-flow computed as if there was no IMG ($i.e.$ the benefit cash-flow linked to the investment) for each year y. Fig. 5.10 shows the results for LT plan 1 Ψ_1 (which is an average and representative configuration).

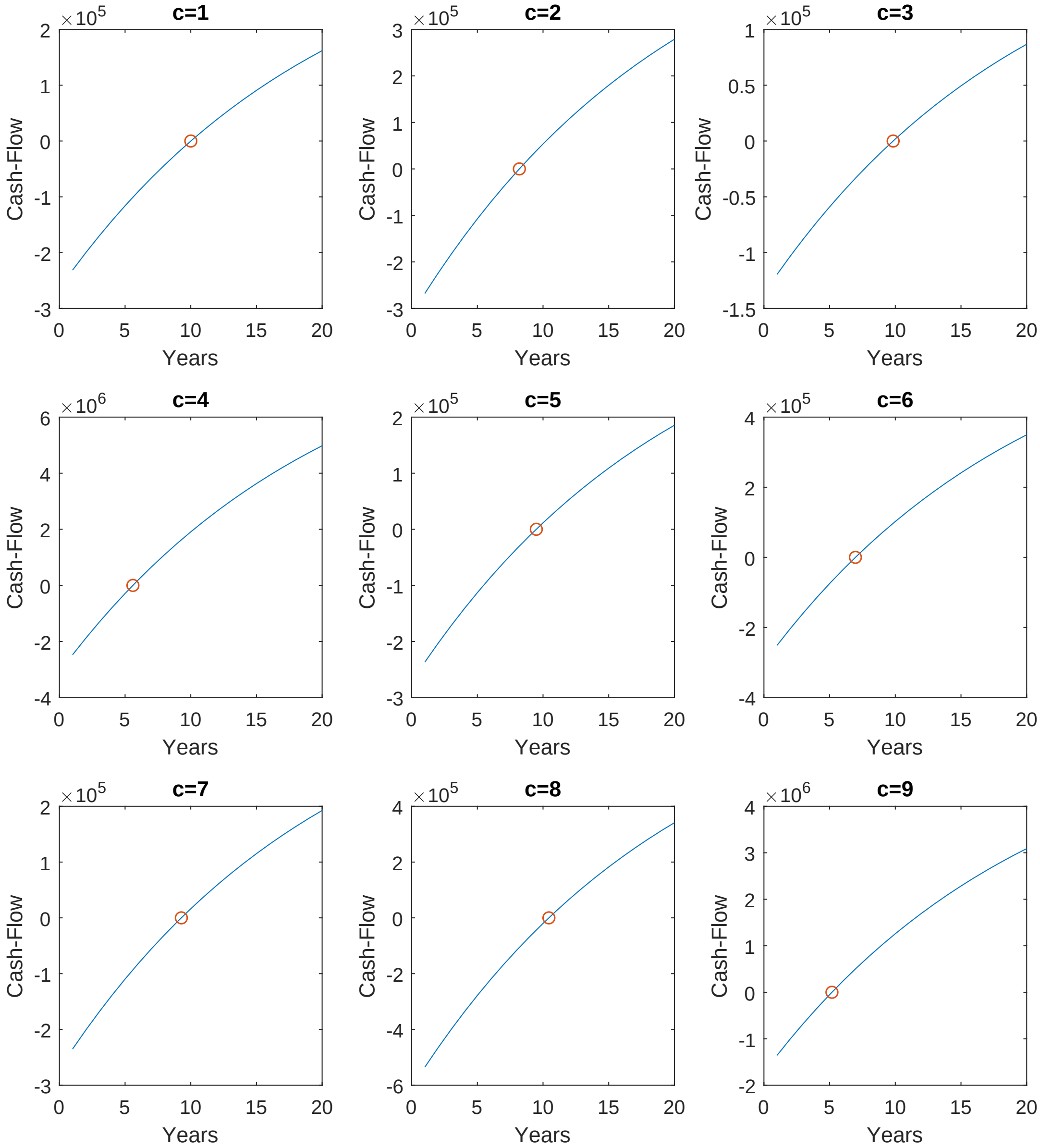


Figure 5.10 – $ROI_{\mu g,c}$ of all companies c for LT plan 1 Ψ_1.

We can observe that the time of return on investment is globally located between 5 and 10 years (closer to 5 years for companies 4 and 9 while closer to 10 years for companies 1, 3, 5 and 8) which are realistic values.

5.7.2 LT plans simulations with unlimited investments

Objective: run the entire tool for the 3 LT pricing plans with unlimited investments (LT plan 1 unlimited, LT plan 2 unlimited and LT plan 3 unlimited) according to the 9 scenarios (Ψ_1 to Ψ_9).

For the following simulations, the inputs of the tool (see Tab. 5.5) are unchanged excepting the budget, the area and the r_{peak}. Indeed, almost unlimited budgets and area have been set as to allow an higher amount of investments. Moreover, the r_{peak} values of the companies have been set to 3, which means that they can invest 3 times more than their own load peak. The new maximum investments possibilities are presented in Tab. 5.26.

s	l_c^{peak} [kW]	$PV_{invest,max}$ [kW]	$WT_{invest,max}$ [kW]	ρ_c^{LT} max [k€]
c=1	206	617	0	738.6
c=2	211	474	158	903.7
c=3	106	318	0	395.1
c=4	2095	1257	5027	7894
c=5	212	636	0	759.1
c=6	324	0	973	1567
c=7	211	632	0	754.8
c=8	418	940	313	1687
c=9	1096	0	3287	4635

Table 5.26 – Maximum long-term investments information with the unlimited constraints.

These simulations with unlimited investment capabilities have been realised with the LT pricing plans 1, 2 and 3 and for all scenarios.

LT plan 1 with unlimited investments

In these simulations, as shown in Tab. 5.27, **the LT equilibrium** is only the node 27 for scenarios Ψ_2, Ψ_4, Ψ_5 and Ψ_8 ($i.e.$ when either the loads or the prices increase, or both of them). For this LT node, the total installed capacity is about $14632kW$, $i.e.$, as expected, about 3 times the power peak of the IMG. The equilibrium is the LT node 18 for the scenario Ψ_8. This node corresponds to 50% of investment for the PV investors and 100% for the others. The total installed capacity is then reduced to $13531kW$. Regarding the other scenarios, the LT equilibrium node is the node 9, $i.e.$ the PV investors do not have to invest, and the total installed capacity is hence decreased to $12429kW$, which remains quite significant.

Regarding **the percentage of losses and savings** in Tab. 5.28, they are quite debatable. Indeed, the percentages of losses of the MGEM/DSO are really significant with those investments. On the other hand, the percentages of savings of the investor companies 2 and 8 are increased and even drastically increased for companies 4, 6 and 9. For the other companies, the gains are quite stable compared with the limited investments.

This can be explained by analysing **the self-consumption** rates in Tab. 5.32, the REP among **the internal metrics** in Tab. 5.30 and **the external exchanges metrics** in Tab. 5.31. Indeed, the REP is much higher than 1 for all scenarios. It is obviously the lowest for the scenarios with the LT node equilibrium 9. This leads to really low SCRs (almost always under 45% except for the company 2) and therefore to a higher SP than PP. This decrease of electricity purchase to the main grid is, of course, the major reason of the significant losses for the DSO. As the investors companies are not able to self-consume their own generation, the exchanges inside the IMG are increased (from around 70% with limited investments to approximately 90% in this case) as well as the SP to the main grid, which explains their huge benefits.

Regarding **the daily pricing** in Tab. 5.29, constant price is mainly chosen (a little more often than for the LT plan 1 with limited investments) and still followed by the cases 1 and 3 as previously.

In fact, **these unlimited investments lead to an other behaviour of the IMG seen from the outside. The amount of RESs installed is such that the benefits repartition could be redesigned as well as the quantification of the benefits for services to the main network and the DSO**. Also, the investment costs are really high and therefore probably unrealistic for the companies without any additional financial aids.

LT plan 2 with unlimited investments

For this second LT plan with unlimited investments, LT node 9 is only chosen for the scenarios Ψ_1, Ψ_3, Ψ_6 and Ψ_9, *i.e.* mainly when the prices decrease.

The observations are quite similar to the previous ones: the percentages of benefits for the investor companies can be really important, especially when the loads and/or the prices decrease. The daily pricing in Tab. 5.35, the internal exchanges parameters in Tab. 5.36 and the external exchanges parameters in Tab. 5.37 confirm the previous observations. The self-consumption rates in Tab. 5.38 are still globally under 50%, except for the second company.

LT plan 3 with unlimited investments

With the LT plan 3 unlimited, the LT node 27 is only chosen for the scenario Ψ_5, *i.e.* when both the loads and the prices are increasing. LT node 18 is chosen for scenarios Ψ_2 and Ψ_8, which are the two other scenarios with an increase of the prices. Otherwise, the LT node 9 is chosen. For all the other results, the analysis remains similar to the previous cases. Note that, as for the LT plan 3 with limited investments, constant daily price inside the IMG is almost always chosen.

With this last simulation, we can conclude that **the PV investments are always penalised by the LT decision making process**. Indeed, LT nodes 9 and 18 are restricting the investments in PV installations. This is realistic given that the used data are from Belgium and therefore the solar irradiation is not optimal in our regions. Moreover, the costs of such investments could be revised and made more interesting thanks to financial investment aids (in addition to the GCs). Consequently, the WT investment seems more interesting. Note that this results could vary according to the WT generation profile used, because the wind profiles are quite unstable. Therefore, it could be interesting to perform the same simulation with a lower WT generation. The latter can be define as a *key factor* to be analysed further in this chapter.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
Eq.	9	27	9	27	27	9	18	27	9
$\sum I_{simu,d}$	5302	12560	4896	59673	29455	59673	24973	41528	24701

Table 5.27 – LT plan 1 unlimited - Equilibrium and number of simulated days analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
MGEM	-17.4	-23.5	-18.8	-12.4	-23.6	-17.0	-18.8	-16.8	-20.8
c=1	-26.1	-27.3	-25.0	-22.5	-30.3	-23.3	-23.7	-30.0	-26.1
c=2	-56.2	-60.1	-52.9	-55.6	-56.9	-53.6	-68.0	-69.8	-64.4
c=3	-25.7	-34.7	-25.1	-30.6	-37.2	-23.5	-31.2	-39.1	-26.1
c=4	-175	-155	-192	-183	-163	-191	-180	-173	-191.8
c=5	-22.4	-26.1	-21.9	-22.4	-28.4	-20.4	-22.8	-28.4	-22.8
c=6	-535	-460	-675	-413	-344	-504	-839	-675	-1082
c=7	-22.32	-26.1	-22.0	-22.4	-27.7	-20.2	-22.9	-28.0	-22.7
c=8	-63.9	-74.2	-54.8	-67.1	-71.4	-60.7	-82.6	-88.8	-71.7
c=9	-208.5	-172	-212	-258	-196	-214	-242	-218	-253

Table 5.28 – LT plan 1 unlimited - Gains/losses analysis for each scenario [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
1	8.24	8.19	8.32	9.04	9.06	8.48	7.93	8.55	8.15
2	89.17	86.04	88.74	85.54	85.39	88.41	86.63	84.41	88.94
3	2.23	4.12	2.67	4.54	4.69	2.97	3.94	5.16	2.37
4	0.36	1.64	0.26	0.88	0.86	0.14	1.50	1.88	0.55

Table 5.29 – LT plan 1 unlimited - Daily pricing percentages [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
TIC [kW]	12429	14632	12429	14632	14632	12429	13531	14632	12429
REP [%]	1.47	1.51	1.38	1.40	1.45	1.27	1.58	1.61	1.52
IEP [%]	90.25	82.99	89.83	82.54	82.54	88.35	85.99	83.2	91.74

Table 5.30 – LT plan 1 unlimited - Internal exchanges analysis.

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
PP [%]	45.66	43.44	48.50	46.28	45.05	51.80	42.38	41.42	44.65
SP [%]	54.34	56.56	51.50	53.72	54.95	48.20	57.62	58.58	55.35

Table 5.31 – LT plan 1 unlimited - External exchanges analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
c=1	NA	42.31	NA	46.47	44.54	NA	50.09	35.74	NA
c=2	66.04	63.67	67.42	75.01	75.56	75.04	56.65	58.60	59.11
c=3	NA	36.71	NA	41.62	40.05	NA	45.95	31.35	NA
c=4	41.74	45.24	47.60	46.62	44.59	47.58	46.44	44.86	45.62
c=5	NA	48.67	NA	55.70	54.74	NA	62.04	42.45	NA
c=6	24.97	22.84	26.06	30.06	30.50	30.36	19.87	20.78	21.71
c=7	NA	54.06	NA	59.70	57.15	NA	64.49	46.36	NA
c=8	33.58	34.70	30.58	39.78	37.71	35.77	29.35	30.55	27.07
c=9	38.46	41.49	41.09	38.56	38.93	41.28	32.02	40.41	38.67

Table 5.32 – LT plan 1 unlimited - Self-consumption rates [%].

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
Eq.	9	27	9	27	27	9	27	27	9
$\sum I_{simu,d}$	5082	10377	4767	64376	62676	26606	43011	41233	23679

Table 5.33 – LT plan 2 unlimited - Equilibrium and number of simulated days analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
MGEM	-13.2	-19.6	-14.2	-16.6	-23.2	-9.95	-24.5	-22.1	-17.8
c=1	-21.7	-27.5	-21.7	-23.1	-31.2	-20.8	-21.6	-33.7	-23.5
c=2	-55.3	-58.7	-54.8	-56.3	-57.7	-53.6	-68.3	-71.2	-64.9
c=3	-22.4	-35.1	-21.7	-30.9	-37.9	-21.2	-32.4	-43.3	-23.5
c=4	-168	-151	-185	-197	-159	-195	-178	-173	-199
c=5	-18.6	-25.1	-17.9	-21.8	-27.8	-17.7	-21.2	-30.4	-19.9
c=6	-550	-463	-737	-435	-364	-512	-871	-696	-1125
c=7	-18.6	-24.6	-18.1	-21.6	-26.9	-17.8	-21.2	-29.3	-19.7
c=8	-65.3	-75.8	-61.6	-71.7	-76.76	-63.0	-86.8	-95.4	-76.8
c=9	-188	-181	-219	-212	-188	-258	-214	-188	-231

Table 5.34 – LT plan 2 unlimited - Gains/losses analysis for each scenario [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
1	24.73	23.57	23.30	22.43	22.77	24.02	21.79	22.14	23.60
2	66.55	58.76	68.03	59.18	59.66	66.05	57.32	57.67	68.03
3	8.44	16.72	8.44	17.66	16.83	9.84	19.34	18.71	8.04
4	0.28	0.94	0.23	0.73	0.73	0.09	1.54	1.48	0.33

Table 5.35 – LT plan 2 unlimited - Daily pricing percentages [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
TIC [kW]	12429	14632	12429	14632	14632	12429	14632	14632	12429
REP [%]	1.33	1.44	1.36	1.41	1.41	1.30	1.72	1.68	1.51
IEP [%]	90.39	83.27	90.49	82.44	82.88	88.20	82.85	82.73	91.71

Table 5.36 – LT plan 2 unlimited - Internal exchanges analysis.

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
PP [%]	49.54	45.31	48.94	46.03	46.20	50.96	39.06	39.92	45.00
SP [%]	50.46	54.69	51.06	53.97	53.80	49.04	60.94	60.08	55.00

Table 5.37 – LT plan 2 unlimited - External exchanges analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
c=1	NA	40.84	NA	44.75	44.20	NA	36.44	36.42	NA
c=2	67.35	65.55	66.25	76.02	75.64	75.69	57.56	58.31	59.11
c=3	NA	35.90	NA	40.35	39.91	NA	31.85	31.68	NA
c=4	48.04	50.90	47.71	46.03	45.79	46.18	41.46	42.79	44.99
c=5	NA	47.85	NA	55.01	54.57	NA	42.73	42.76	NA
c=6	26.02	24.18	24.91	30.86	30.59	31.15	20.73	21.46	21.80
c=7	NA	52.39	NA	57.44	56.64	NA	47.17	46.92	NA
c=8	31.12	33.02	32.71	38.02	37.68	36.28	31.60	31.64	27.12
c=9	42.22	38.91	41.10	39.62	40.50	40.35	37.57	38.05	39.20

Table 5.38 – LT plan 2 unlimited - Self-consumption rates [%].

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
Eq.	9	18	9	9	27	9	9	18	9
$\sum I_{simu,d}$	4805	8484	5497	28922	63761	30185	25281	46550	24349

Table 5.39 – LT plan 3 unlimited - Equilibrium and number of simulated days analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
MGEM	-26.6	-28.6	-25.3	-24.8	-23.5	-29.7	-21.01	-30.8	-31.0
c=1	-27.4	-26.9	-27.2	-26.8	-29.1	-26.9	-28.8	-29.1	-29.4
c=2	-56.1	-58.4	-52.1	-55.6	-56.8	-53.2	-65.4	-67.6	-63.2
c=3	-28.2	-32.8	-27.3	-27.2	-36.0	-27.5	-28.9	-35.7	-29.4
c=4	-171	-163	-179	-173	-166	-184	-180	-164	-184
c=5	-24.5	-26.1	-24.1	-24.0	-28.4	-24.5	-25.3	-28.0	-26.2
c=6	-516	-426	-643	-393	-328	-473	-763	-615	-998
c=7	-24.9	-25.9	-24.3	-24.2	-28.2	-24.6	-25.3	-27.9	-26.1
c=8	-60.2	-66.7	-51.1	-64.4	-67.3	-56.0	-74.6	-80.4	-65.9
c=9	-188	-170	-198	-206	-204	-232	-204	-183	-219

Table 5.40 – LT plan 3 unlimited - Gains/losses analysis for each scenario [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
1	0.09	0.02	0.05	0.05	0.08	0.02	0.03	0.04	0.02
2	99.58	98.82	99.67	99.64	98.78	99.72	99.29	98.39	99.27
3	0.10	0.12	0.04	0.09	0.09	0.09	0.07	0.10	0.12
4	0.23	1.04	0.24	0.22	1.05	0.17	0.61	1.47	0.59

Table 5.41 – LT plan 3 unlimited - Daily pricing percentages [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
TIC [kW]	12429	13531	12429	12429	14632	12429	12429	13531	12429
REP [%]	1.41	1.48	1.34	1.32	1.41	1.33	1.48	1.62	1.56
IEP [%]	89.94	85.78	90.24	88.55	82.33	88.48	91.73	85.93	91.95

Table 5.42 – LT plan 3 unlimited - Internal exchanges analysis.

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
PP [%]	47.85	44.67	49.32	49.93	46.15	49.68	45.78	41.32	43.34
SP [%]	52.15	55.33	50.68	50.07	53.85	50.32	54.22	58.68	56.66

Table 5.43 – LT plan 3 unlimited - External exchanges analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
c=1	NA	52.93	NA	NA	46.66	NA	NA	49.55	NA
c=2	66.74	67.60	66.83	76.02	75.06	75.68	58.19	57.24	58.38
c=3	NA	49.96	NA	NA	41.79	NA	NA	45.62	NA
c=4	45.45	44.73	47.54	47.03	44.65	45.73	45.61	45.17	43.89
c=5	NA	68.77	NA	NA	56.01	NA	NA	61.81	NA
c=6	25.49	26.30	25.66	31.06	30.02	30.79	21.01	20.28	21.26
c=7	NA	68.08	NA	NA	59.55	NA	NA	63.59	NA
c=8	31.82	30.11	30.61	36.31	40.64	36.85	27.98	27.21	27.61
c=9	41.36	41.27	43.36	36.58	40.79	37.54	40.40	37.92	37.02

Table 5.44 – LT plan 3 unlimited - Self-consumption rates [%].

Time of return on investment analysis

Regarding the times of return on investment (see Fig. 5.11), the results are more debatable than with limited investment capabilities. Indeed, 3 groups can be defined: the first one is composed of companies 1, 3, 5, 7 and 8 with a ROI of more than 10 or even 15 years, which are high values, that could make the companies reluctant for the investments. That is the reason why the node 27 is not chosen for this scenario (and lots of other scenarios with unlimited investments). The second group is the company 2, with a ROI of about 10 years, which is quite a high value as well but still realistic. The last group is composed of the remaining three companies (*i.e.* companies 4, 6 and 9), for which such investments profitability has already been presented with the previous results and is confirmed according to the low values of ROI (around 5 years).

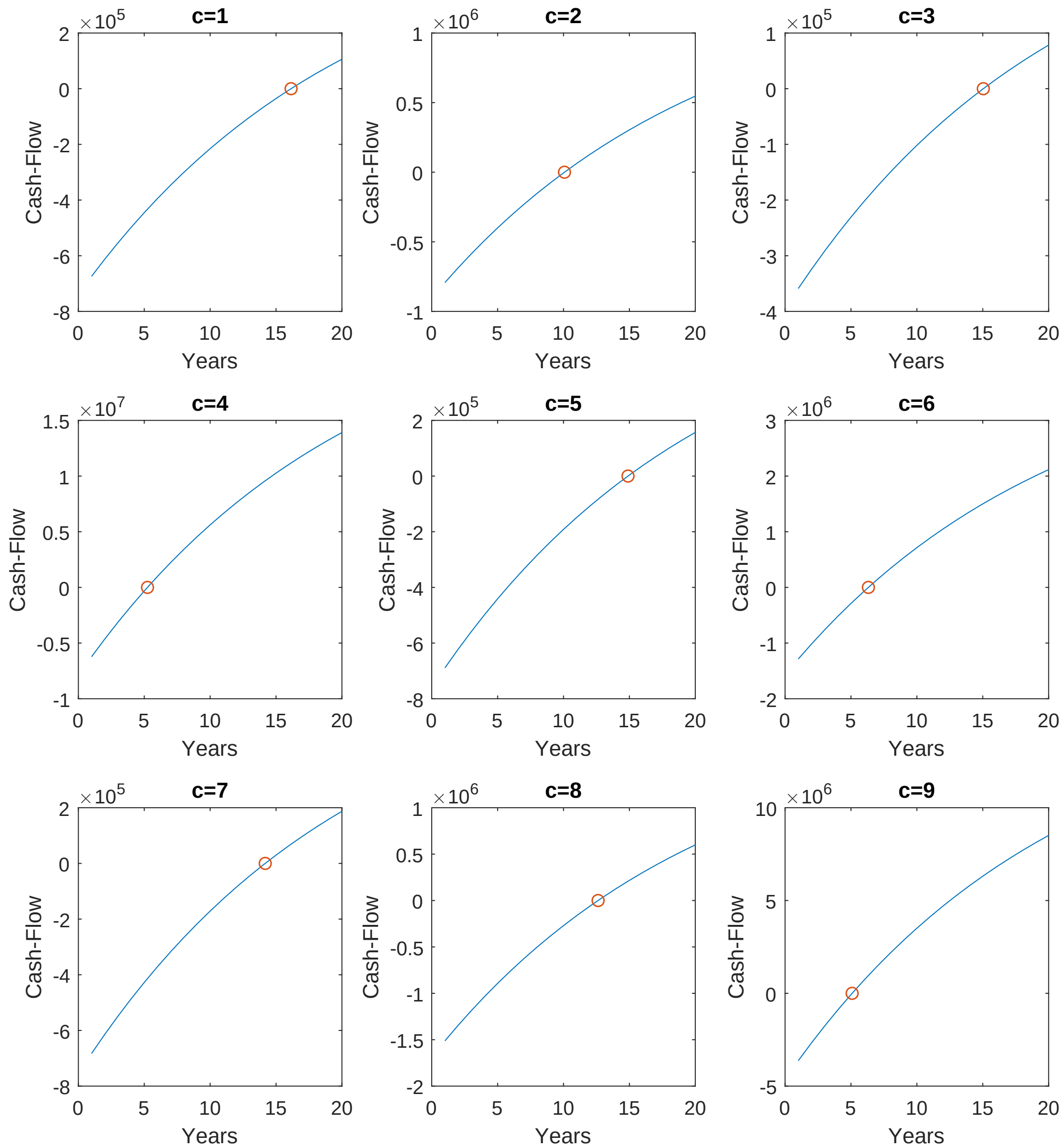


Figure 5.11 – $ROI_{\mu g,c}$ of all companies c for LT plan 1 Ψ_1 unlimited.

5.7.3 LT investigations application

Objective: select some interesting LT plans and scenarios among the simulations performed in the two previous section (limited and unlimited investments) to apply the defined investigations, *i.e.* LM, shared investments and the use of a shared ESS.

As described in the first part of this chapter, some *LT investigations* are realised on some configurations of the IMG. They concern the application of LM and the possibility of shared investments (in RESs and ESSs). According to the kind of investigation, the application case will be different, as discussed in the remaining of this section.

LT investigations: Load Management

As previously mentioned, LM application is not relevant over the 20 years of planning on the scenarios considering a load profile evolution. Indeed, the uncertainties over the long-term time horizon are such that, it does not make sense to give advices to companies regarding their possibilities of performing LM with the uncertain load profiles. Therefore, LM is performed only for the scenario Ψ_1 and for the LT equilibrium node found in the previous simulations. Remember that the companies that have the possibility of performing LM are companies 1, 3, 6, 7 and 8. LM is carried out for each simulated day (*i.e.* $\sum_d I_{simu,d}$ times) and then, the new daily mean cash-flow value is computed and extended over 1 year.

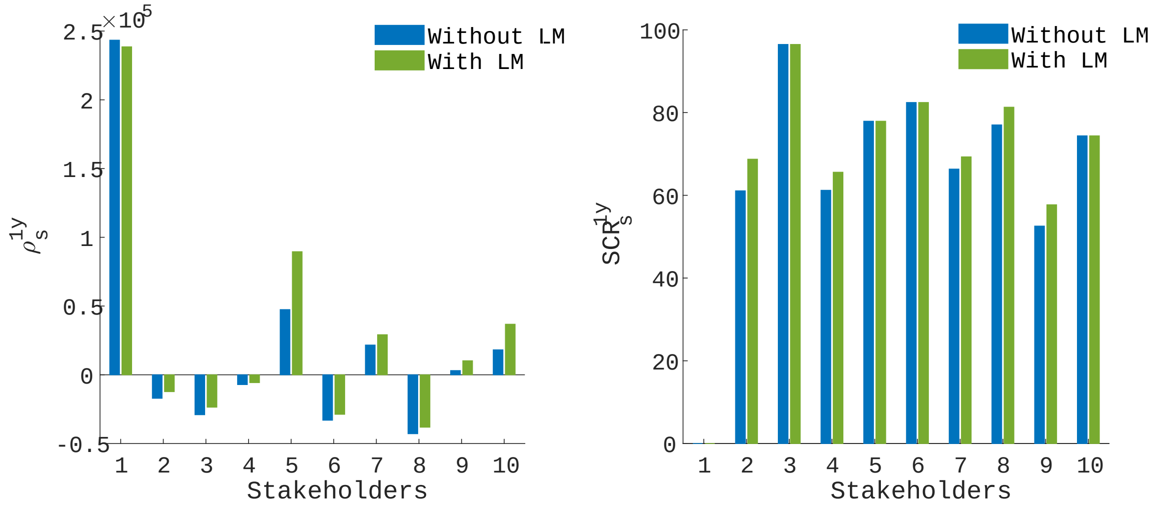
The simulations have been run twice:

- **The first simulation ignores the daily pricing decisions (fixed prices)**, *i.e.* the previously decisions have been saved and unchanged. The only impact of LM is thus evaluated in this simulation;
- **The second simulation is realised with the whole ST game including LM and daily pricing decisions** in order to see if the impact of LM is modified and how the pricing decisions influence it.

Simulation with fixed prices: The results for the LT plan 1 Ψ_1 are shown below and analysed through four parameters:

- Fig. 5.12a depicts the cash-flow value for each stakeholder s over 1 year (ρ_s^{1y}) without LM (results from previous LT 1 plan simulation) and with LM. For every stakeholders, LM is economically interesting if the ρ_s^{1y} value is the highest. We can therefore see that, except for the DSO/MGEM (stakeholder 1), LM is interesting for all the stakeholders, including the ones that are not performing LM. This can be explained thanks to the new methodology of load peak computation (described in chapter 2) applied in the context of LM. The global peak of the IMG is reduced thanks to LM and this decrease is spread over all the stakeholders in a community spirit. This is done in spite of the MGEM/DSO given that with LM the benefits linked to the load peak are logically decreased;
- Fig. 5.12b shows the self-consumption rates of the companies. Of course, the ones of the companies that are not performing LM remain unchanged while the one of all the

other companies is increased byf several percents. This analysis can also explain the small decrease of the gains of the MGEM/DSO because if the self-consumption is increased inside the IMG, that means that the amount of electricity exchanged inside the IMG and with the main grid is decreased;



(a) Cash-flows over 1 year. (b) Self-consumption rates.

Figure 5.12 – LT plan 1 Ψ_1 with fixed prices.

- Tab. 5.45 gathers the accurate benefits percentage of each company and the loss for the MGEM/DSO. If the ρ_s^{1y} value is positive, a positive $\%_s^{1y}$ value means a benefit while if the ρ_s^{1y} value is negative, a negative $\%_s^{1y}$ value means a benefit. Those results are in accordance with the ones in Fig. 5.12;

	MGEM	c=1	c=2	c=3	c=4	c=5	c=6	c=7	c=8	c=9
$\%_s^{1y}$	-1.99	-23.31	-18.86	-20.04	+88.81	-13.02	+34.72	-11.04	+232.9	+102.5

Table 5.45 – LT plan 1 Ψ_1 with fixed prices - Gains/losses percentages over 1 year.

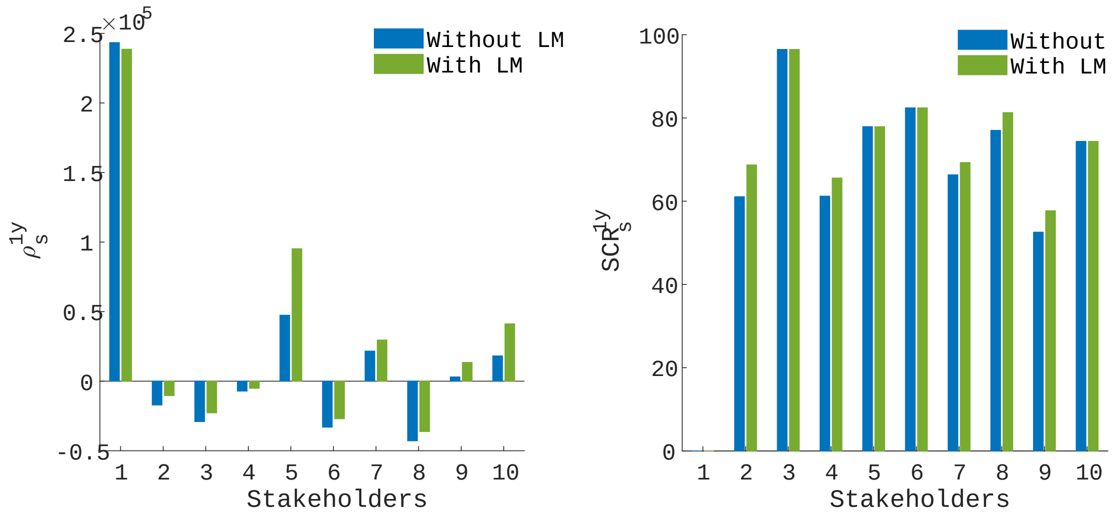
- Finally, the occurrence of LM, *i.e.* the percentage of days d for which doing LM is chosen, denoted $\%_{d,c}$ for each company c, is presented in Tab. 5.46. We can see that for the five companies concerned, performing LM is most of the time chosen.

s	$\%_{1,s}$	$\%_{2,s}$	$\%_{3,s}$	$\%_{4,s}$	$\%_{5,s}$
c=1	86.47	81.80	59.88	81.51	79.73
c=3	67.74	83.07	80.85	65.52	64.38
c=6	82.74	81.68	77.58	83.30	76.70
c=7	66.08	85.29	73.25	61.75	51.64
c=8	96.21	99.38	99.13	88.51	86.89

Table 5.46 – LT plan 1 Ψ_1 with fixed prices - LM occurrence over 1 year.

Simulation with daily pricing choice: For the second LM application on LT plan 1 Ψ_1 with daily pricing, the results are presented exactly in the same way in Fig. 5.13a, Fig. 5.13b, Tab. 5.47 and Tab. 5.48. The most interesting results compared to the previous LM simulation with fixed prices concern the percentages of gains/losses. Indeed, we can see that the benefits are increased for all the companies thanks to the adaptation of the daily pricing. The LM occurrence remains quite the same.

Regarding the daily pricing choices repartition, it remains quite similar to the LT plan 1 Ψ_1 without LM. No drastic changes are observed: the case one is chosen about 20% of the time, the second one about 72% of the time and the third one about 6% of the time.



(a) Cash-flows over 1 year.

(b) Self-consumption rates.

Figure 5.13 – LT plan 1 Ψ_1 with daily pricing.

	MGEM	c=1	c=2	c=3	c=4	c=5	c=6	c=7	c=8	c=9
$\%_s^{1y}$	-1.96	-39.41	-21.71	-28.48	+100.8	-18.34	+36.80	-15.51	+339.9	+126.9

Table 5.47 – LT plan 1 Ψ_1 with daily pricing - Gains/losses percentages over 1 year.

s	$\%_{1,s}$	$\%_{2,s}$	$\%_{3,s}$	$\%_{4,s}$	$\%_{5,s}$
c=1	86.57	81.60	59.92	81.58	79.31
c=3	67.79	82.95	80.78	65.49	63.71
c=6	82.84	81.56	77.51	83.17	76.21
c=7	65.88	85.25	73.18	61.49	51.76
c=8	96.16	99.23	98.86	88.25	86.23

Table 5.48 – LT plan 1 Ψ_1 with daily pricing - LM occurrence over 1 year.

For the interested reader, the detailed results for this plan as well as for LT plan 2 and 3 are shown in the Appendix D.

Given the promising results of the LM application, **it could be interesting to see, for information only, its impact on the decision making process regarding the LT investments when the "classical" decision is not to invest at** 100% **of the investment possibilities** (*i.e.* **when the LT node is different from node** 27). For example, it is the case for the LT plan 1 Ψ_1 with unlimited investments.

In order to see the impact of LM, the results have to be extended to 20 years. For that purpose, the NPVs have to be computed by (3.4), taking into account the new mean daily cash-flows, extended to 20 years instead of 1 year as previously realised in this section. Once the NPVs (η_s) are computed for each stakeholder s and for all simulations, the ones without and with LM can be compared. This principle has been applied for the **LT plan 1** Ψ_1 **with unlimited investments for both LT nodes** 9 **and** 27. Indeed, in Tab. 5.28, we have shown that the equilibrium node for the first scenario was the LT node 9. The goal of this analysis is then to see if, with LM, the LT node 9 is still more interesting than the LT node 27 (with LM as well).

All the generated η_s values are shown in Fig. 5.14. The first value is the one of the LT node 9 without LM (*i.e.* the one relative to Tab. 5.28), the second one is for the same node with LM. The two last ones are for the LT node 27 without (*i.e.* also relative to Tab. 5.28) and with LM, respectively. We can clearly observe that:

- LM leads to some benefits for both nodes (more gains for the stakeholders with positive η_s values and less expenses for the ones with negative values);
- As the node 27 leads to more investments regarding PV, additional LM can be performed and the benefit is still increased.

<textbfIf the global LT game is performed with those new NPVs for nodes 9 and 27, the new equilibrium is now the LT node 27. That means that, performing LM would lead to a change of decision. This simulation has been realised for information only. **Those results are just illustrative and must be considered carefully.** Indeed, as previously explained, giving advices relative to LM in a 20 years time horizon is quite difficult and uncertain.

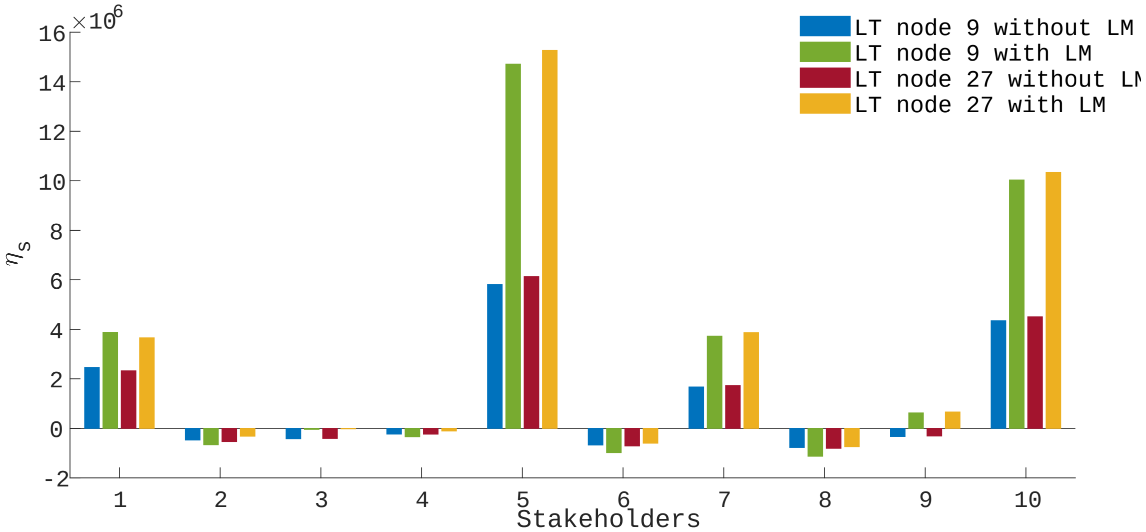


Figure 5.14 – NPV over 20 years with LM for LT nodes 9 and 27.

LT investigations: shared investments

As previously explained, the shared investments can be seen in two ways: the first one is a joint investment of individually sized installations and the second one is the associated investments sized by the MGEM. Therefore, this investigation is divided in two main parts:

- The joint investments are considered, on the one hand, for the LT plan 1 Ψ_1 with limited investments to see the impact on the percentages of gains/losses, and, on the other hand, for the LT plan 1 Ψ_1 with unlimited investments to investigate if it could imply a change of LT decision;
- The associated investments is then only shown for the LT plan 1 Ψ_1 in order to evaluate the behaviour of the tool with this change of perspective.

Joint investments: regarding this vision of investments, the sizing of the RESs is not changed compared to the previously described methodology. Therefore, the only changes occur for the η_s values (given that the LT cash-flow is changed according to the new investment cost) and thus potentially for the LT equilibrium.

For the **LT plan 1 Ψ_1 (with limited investments)**, as the LT node with the LT plan 1 was already the node 27, the joint investments can not change the LT equilibrium. The comparison must be carried out only in terms of saving percentages for the companies (there is no influence on the percentage of the MGEM as he is not concerned by the investments). In Fig. 5.15, we can observe that the percentages of savings of all the stakeholders are increased of several percent (around 10%) except for the ninth stakeholder, for which the savings are about 25%.

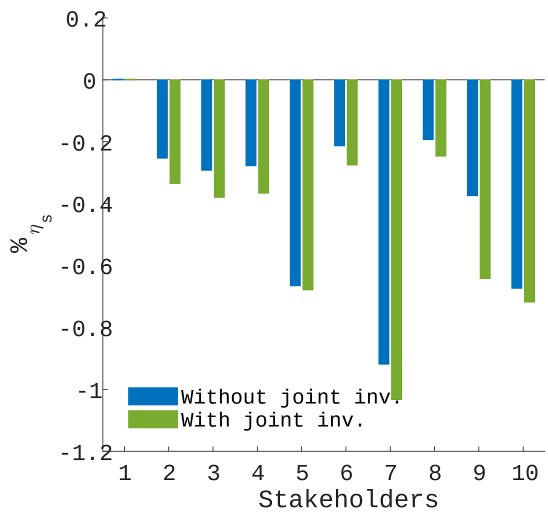


Figure 5.15 – LT plan 1 with limited investments - Joint investments

In order to observe the impact of the joint investments in the case of unlimited investments, the previously described principle has been applied for the **LT plan 1 Ψ_1 unlimited**. For this scenario, the LT decision was initially the node 9.

With joint investments, the LT equilibrium is now the node 27. That means that the decrease of the costs considered is enough to change the investments and therefore, the maintenance costs (computed from the investment cost), to massively invest in the IMG. The decisions taken are therefore significantly impacted by the considered costs.

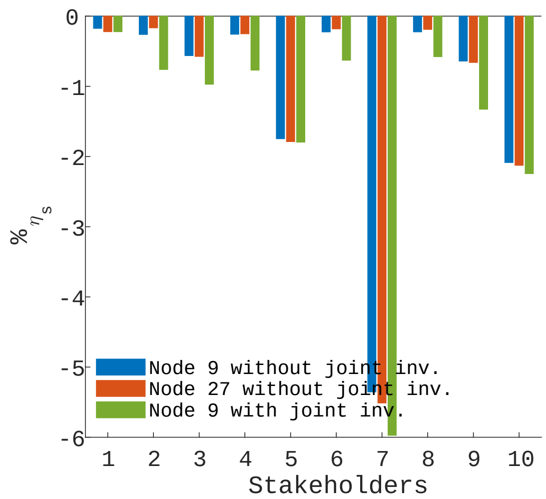


Figure 5.16 – LT plan 1 unlimited - Joint investments

Fig. 5.16 shows the percentages of losses and savings of the NPVs for all stakeholders s, $\%_{\eta_s}$ for the basic LT nodes 9 and 27 (decisions initially taken) as well as the new LT node 27 with joint investments (new decision taken). We can observe that, for all the companies ($s = 2, ..., 10$), savings of several percent are realised thanks to the joint investments.

The analysis parameters are shown in the tables below. The main differences occur for the REP, that is obviously increased due to the decision taken and the daily pricing trends. The SP is therefore even more increased (energy is sold almost 60% of the time).

s	$\%_{\eta_s}$	SCR [%]
MGEM	-22.1	NA
c=1	-75.9	42.2
c=2	-97.0	64.7
c=3	-76.9	37.0
c=4	-179	40.6
c=5	-62.7	49.2
c=6	-597	23.7
c=7	-57.7	54.2
c=8	-133	36.3
c=9	-224	36.9

Table 5.49 – LT plan 1 Ψ_1 unlimited - Gains/losses percentages and SCRs.

1	2	3	4
7.98	86.06	4.52	1.44

Table 5.50 – LT plan 1 Ψ_1 unlimited - Daily pricing trends [%].

TIC [kW]	REP [%]	IEP [%]	PP [%]	SP [%]
14632	1.64	82.8	40.60	59.40

Table 5.51 – LT plan 1 Ψ_1 unlimited - Metrics analysis.

Associated investments: with this kind of shared investments, the possibilities of investments are different at each LT node. The sizing of the WT and PV investments are realised according to the global investments budget and load peaks of all the companies. The participation of each company is computed according to his load peak weight among the global one.

In that way, the obtained LT equilibrium is the LT node 15 with a TIC of $4319kW$. For information, for the LT nodes already obtained (9, 18 and 27), the TICs are, with the associated investments, of 5025kW and 5426kW, respectively. The new LT decision taken is therefore the closest one compared to the decision taken with the LT plan 1 considering individual investments ($4699kW$).

s	l_s^{peak} [kW]	PV_{invest} [kW]	WT_{invest} [kW]	ρ_c^{LT} [k€]
c=1	206	62	120	238.7
c=2	211	63	123	244.1
c=3	106	32	62	123.3
c=4	2095	629	1226	2434
c=5	212	64	124	246.6
c=6	324	97	190	376.7
c=7	211	63	123	244.28
c=8	418	125	245	485.6
c=9	1096	329	642	1274

Table 5.52 – Long-term investments for LT node 15 with the associated investments.

For the LT node 15, the possibilities of investments are shown in Tab. 5.52. Every stakeholders are is investing, at least a little amount, in both the PV and the WT shared installations. The LT cash-flows are computed and we can observe, compared to Tab. 5.7, that they are globally lower but remain close to the values with individual investments. The remaining parameters, for their part, stay almost unchanged.

s	$\%_{\eta_s}$	SCR [%]
MGEM	-6.33	NA
c=1	-67.9	69.4
c=2	-50.7	94.1
c=3	-76.2	81.2
c=4	-54.1	76.2
c=5	-55.8	93.9
c=6	-138	53.6
c=7	-48.3	92.2
c=8	-88.8	63.0
c=9	-73.0	76.7

Table 5.53 – LT plan 1 Ψ_1 with associated investments - $\%_{\eta_s}$ and SCRs.

1	2	3	4
19.51	74.55	5.55	0.39

Table 5.54 – LT plan 1 Ψ_1 with associated investments - Daily pricing trends [%].

TIC [kW]	REP [%]	IEP [%]	PP [%]	SP [%]
4319	52.61	69.36	82.12	17.88

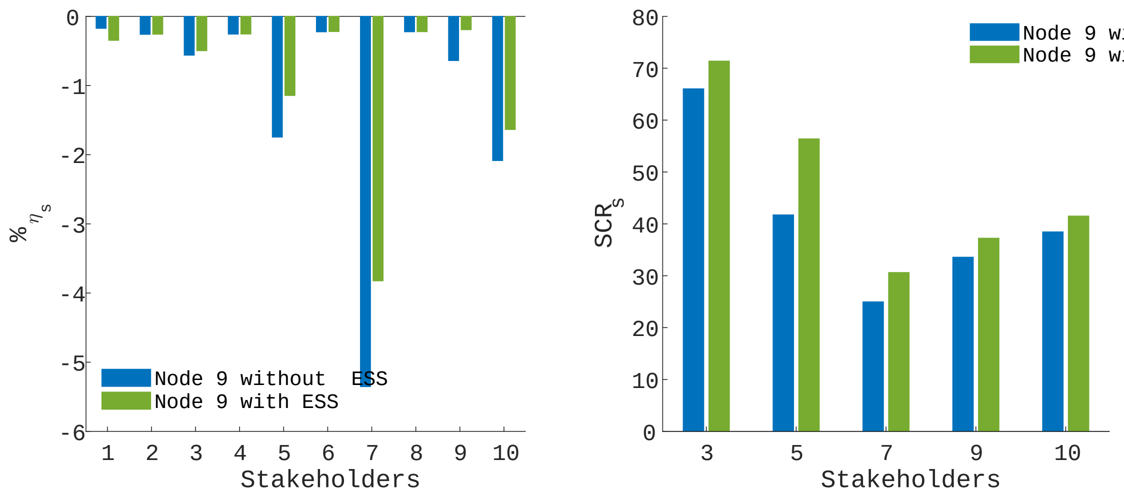
Table 5.55 – LT plan 1 Ψ_1 with associated investments - Metrics analysis.

This example shows that the way of considering the investments and their distribution among the companies leads to a different behaviour of the IMG and other LT decisions.

LT investigations: shared investments with an energy storage system

Again in the vision of sharing investments, the possibility of adding a shared ESS inside the IMG has been simulated. For that purpose, **the joint investments for LT plan** 1 Ψ_1 **unlimited have been conserved and simulated with a shared ESS for both LT node** 9 **(the equilibrium) and LT node** 27 **(to see the impact on the node with the most investments)**.

For both scenarios, the percentages of gains and losses ($\%_{\eta_s}$), the SCRs, the daily pricing trend as well as the internal and external metrics are observed. The ESS costs considered for the ESS remain unchanged compared to chapter 3, *i.e.* with a power cost of 500€/kW and an energy cost of 200€/kWh. The installed ESS capacity is equal to the TIC. The investment cost is shared between the investor companies according to their weight $ESS_{\%,c}$ in the whole installation (as previously explained in section 5.5.3).



(a) Percentages of gains or losses.

(b) Self-consumption rates.

Figure 5.17 – LT plan 1 Ψ_1 unlimited node 9.

For the LT node 9, the stakeholders 3, 5, 7, 9 and 10 are the only investors. Regarding Fig. 5.17a, the losses of the MGEM are increased (stakeholder 1) and the benefits of the investors companies are drastically decreased. However, their SCRs (see Fig. 5.17b) are all increased compared to the basic simulation of LT plan 1 unlimited. That means that the benefit of the ESS is present but not sufficient to balance the important cost of the investments. The other parameters (presented in Tab. 5.56, 5.57 and 5.58) remain similar to those of the previous simulations.

For the LT node 27, all the companies are investing in RESs and therefore in the shared ESS. However, the observations are quite similar than for LT node 9: the SCRs (see Fig. 5.18b) are all increased but the percentages of savings are all decreased (see Fig. 5.18a) given the high investment cost. The stakeholder 4 even makes a loss with such an ESS investment (see Tab. 5.59). Therefore, **the ESS seems to not be profitable for the stakeholders with such a cost and application**. The daily pricing choices are similar to the previous simulations (see Tab. 5.60). Tab. 5.61 shows that, compared to the LT node 9, the REP is obviously increased while the IEP is decreased, leading to more selling to the network (SP is increased).

s	$\%_{\eta_s}$	SCR [%]
MGEM	-34.71	NA
c=1	-25.84	NA
c=2	-49.66	71.38
c=3	-25.53	NA
c=4	-114.4	56.39
c=5	-22.0	NA
c=6	-382.4	30.62
c=7	-22.16	NA
c=8	-19.28	37.24
c=9	-163.6	41.51

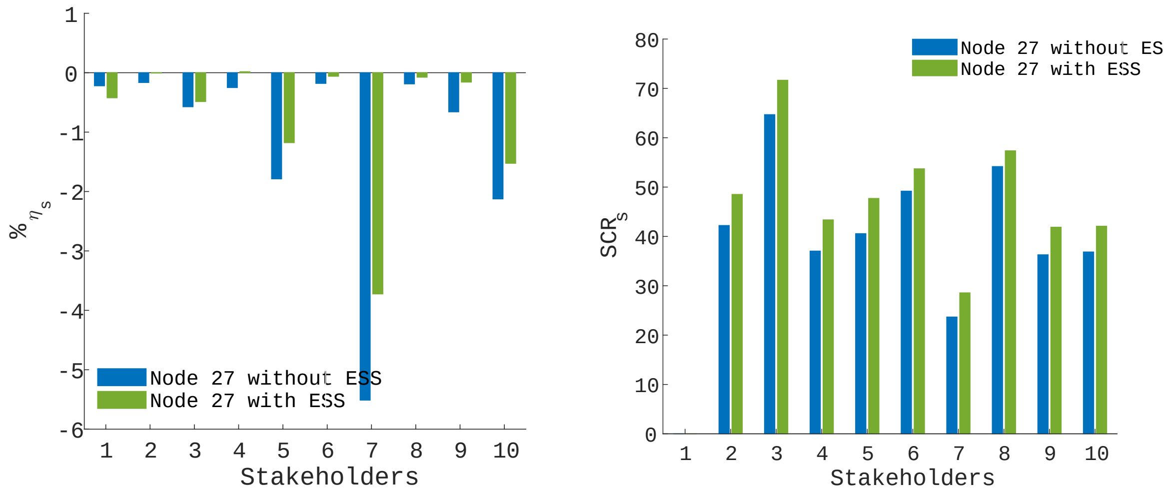
Table 5.56 – LT plan 1 Ψ_1 unlimited node 9 - $\%_{\eta_s}$ and SCRs.

1	2	3	4
8.12	88.92	2.71	0.24

Table 5.57 – LT plan 1 Ψ_1 unlimited node 9 - Daily pricing trends [%].

TIC [kW]	REP [%]	IEP [%]	PP [%]	SP [%]
12429	1.42	90.20	47.51	52.49

Table 5.58 – LT plan 1 Ψ_1 unlimited node 9 - Metrics analysis.



(a) Percentages of gains and losses.

(b) Self-consumption rates.

Figure 5.18 – LT plan 1 Ψ_1 unlimited node 27 - $\%_{\eta_s}$ and SCRs.

s	$\%_{\eta_s}$	SCR [%]
MGEM	-42.26	NA
c=1	-0.65	48.52
c=2	-48.63	71.66
c=3	+1.67	43.37
c=4	-117.8	47.71
c=5	-6.04	53.71
c=6	-372.4	28.58
c=7	-7.62	57.36
c=8	-15.86	41.88
c=9	-152.5	42.08

Table 5.59 – LT plan 1 Ψ_1 unlimited node 27 - $\%_{\eta_s}$ and SCRs.

1	2	3	4
8.35	85.50	4.77	1.38

Table 5.60 – LT plan 1 Ψ_1 unlimited node 27 - Daily pricing trends [%].

TIC [kW]	REP [%]	IEP [%]	PP [%]	SP [%]
14632	1.62	83.13	40.98	59.02

Table 5.61 – LT plan 1 Ψ_1 node 9 - Metrics analysis.

5.7.4 Impacts of the key factors analysis

Objective: all along the previous observations for the 6 LT plans (according to 9 scenarios each one), some key factors have been defined. A deeper study of their impact(s) on the results is performed in this section.

According to the previous observed results and also to our experience, some parameters can really have an impact on the decisions taken by the tool. For that purpose, until now, three key factors have been highlighted and are further analysed below:

- To our knowledge, in the current pricing scheme, the load peak is an important part of the electricity cost. It is also considered in the new pricing inside the IMG but, until now, its price has been fixed. It could be a key factor and therefore the possibility of changing the load peak pricing scheme will be considered in this section;
- As observed in the previous simulations, the daily pricing trends and values have impacts on the ST decisions. The key factor is mainly the second daily trend price ($i.e$ the constant price) inside the IMG, that can be changed (lower or higher values than the one already simulated) in order to assess its influence on the results;
- The WT generation profile is depending on the wind, which is a particularly unstable source. As the LT plans with unlimited investments seem to favour the WT investments, it could be interesting to realise simulations with a lower WT generation in order to observe its influence on the LT decisions.

Load peak price impact

The IMG pricing scheme for the simulations run is the same as for the LT pricing plan 1, at the exception of the power pricing inside the IMG. Indeed, power ratio value r_P was set to 0.1, which is quite a low value. In order to see the impact of a higher value on the ST price decisions, the value is now set to 0.3.

The main impact of such a pricing is for the gains of the MGEM/DSO, as shown in Tab. 5.63. Indeed, a higher peak pricing directly concerns both the incomes of the MGEM and the DSO. For all scenarios, the gains of the companies are slightly decreased but, it is the accumulation of these small differences that leads to benefits for the MGEM/DSO.

Regarding the daily pricing percentages in Tab. 5.64, their values are quite similar than for the basic LT plan 1, as well as the observations for the self-consumption rates (see Tab. 5.67) and the metrics (see Tab. 5.65 and 5.66).

Note that, if LM (with variable daily pricing) is performed with this load peak pricing scheme, the benefits of the companies performing the LM is increased compared to the application of LM on the basic LT plan 1, which shows the importance of the pricing on the LM impact. For the interested reader, the results are presented in Tab. D.11 in the Appendix D.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
Eq.	27	27	27	27	27	27	27	27	27
$\sum I_{simu,d}$	16685	12872	16735	79553	88030	98228	103045	96685	106576

Table 5.62 – LT plan 1 with $r_P = 0.3$ - Equilibrium and number of simulated days analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
MGEM	+6.69	+6.67	+8.03	+9.93	+12.2	+6.72	+5.55	+5.49	+7.08
c=1	-22.9	-24.7	-20.9	-20.7	-21.9	-19.6	-28.7	-29.8	-25.9
c=2	-28.3	-28.2	-26.5	-24.1	-24.5	-24.3	-34.1	-34.2	-32.4
c=3	-26.2	-28.3	-24.2	-24.7	-25.9	-23.2	-31.2	-32.5	-28.4
c=4	-68.7	-60.6	-63.9	-61.1	-63.1	-71.8	-72.1	-58.2	-69.3
c=5	-19.8	-21.1	-18.3	-17.7	-18.7	-16.8	-23.9	-24.8	-21.5
c=6	-89.8	-74.2	-101	-63.6	-57.0	-75.1	-131	-110	-158
c=7	-18.1	-19.2	-16.4	-15.8	-16.8	-15.1	-21.6	-22.4	-19.5
c=8	-34.9	-36.2	-31.9	-31.5	-33.1	-30.6	-43.6	-45.8	-39.9
c=9	-80.3	-84.3	-98.3	-78.9	-66.6	-77.8	-72.9	-76.3	-73.3

Table 5.63 – LT plan 1 with $r_P = 0.3$ - Gains/losses analysis for each scenario [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
1	19.83	19.00	19.19	20.18	20.79	20.82	18.97	19.92	19.54
2	74.29	74.08	74.67	72.96	72.43	71.92	75.03	74.17	74.79
3	5.83	6.88	6.13	6.83	6.77	7.24	5.92	5.83	5.56
4	0.05	0.04	0.00	0.03	0.01	0.02	0.08	0.08	0.11

Table 5.64 – LT plan 1 with $r_P = 0.3$ - Daily pricing percentages [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
TIC [kW]	4699	4699	4699	4699	4699	4699	4699	4699	4699
REP [%]	53.72	53.49	51.83	45.75	46.87	46.17	55.35	54.01	53.54
IEP [%]	70.08	67.49	69.26	65.88	65.40	64.88	72.33	71.91	72.05

Table 5.65 – LT plan 1 with $r_P = 0.3$ - Internal exchanges analysis.

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
PP [%]	82.28	82.15	82.88	87.37	86.53	86.90	80.78	81.50	81.62
SP [%]	17.72	17.85	17.12	12.63	13.47	13.10	19.22	18.50	18.38

Table 5.66 – LT plan 1 with $r_P = 0.3$ - External exchanges analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
c=1	59.04	65.64	62.82	63.17	63.50	62.18	59.74	56.57	58.53
c=2	96.90	97.04	96.01	98.31	98.57	98.42	92.63	92.90	93.16
c=3	59.24	64.59	62.84	65.0	64.98	64.03	57.8	54.63	56.40
c=4	76.54	77.86	80.03	82.49	80.74	81.55	76.25	78.65	76.20
c=5	81.50	84.61	83.34	86.94	86.61	86.13	77.10	74.89	75.70
c=6	68.02	69.15	64.82	73.11	74.34	73.40	58.06	59.90	59.48
c=7	73.59	80.59	78.53	77.32	77.47	77.24	75.32	71.75	74.57
c=8	50.79	57.60	54.93	53.99	53.83	53.31	52.55	49.26	51.63
c=9	72.26	63.94	64.3	70.86	72.54	73.92	70.55	71.42	73.14

Table 5.67 – LT plan 1 with $r_P = 0.3$ - Self-consumption rates [%].

Value of the constant daily price (case 2)

For the 3 LT pricing plans previously analysed, the repartition of the 4 daily pricing cases was different in order to compensate the gains or losses of the MGEM/DSO or the companies. The constant daily price (*i.e.* case 2) is overall the most frequently chosen possibility. In those plans, it is fixed to the average of the outside purchasing electricity price for each day $\pi_{av,day}$ (in chapter 2, see (2.3)).

Therefore, the value of this constant price seems interesting to modify in order to observe its impact on the ST pricing decisions. For that purpose, $\pi_{av,day}$ was alternatively adapted in a lower value and a higher value, respectively defined as:

- the mean of the inside electricity price:

$$\pi_{av,day} = \frac{1}{24} \sum_{h=1}^{h=24} (\pi_{out,p,h} \times r_{in/out}) \tag{5.9}$$

- the maximum of the inside electricity price

$$\pi_{av,day} = max(\Pi_{out,p} \times r_{in/out}) \tag{5.10}$$

Simulations have been performed for the 3 LT pricing plans with limited investments and the scenario Ψ_1 in order to see the impact mainly on the gains/losses of all stakeholders and on the daily pricing trends.

Simulation with low constant price: If the constant price is set to the mean inside price, for the three LT pricing plans, this case is never chosen. That means that the explanations given previously are confirmed: the constant daily price trend is chosen to compensate the losses of the MGEM/DSO in the LT plans 1 and 3. Therefore, a lower value of it does not make any sense for that objective and is therefore never chosen. For the LT plan 2, this trend was already seldom chosen in the previous simulations in order to compensate the benefits of the MGEM/DSO, and the decision trend is validated.

The daily pricing preferences are therefore reorganised: for the LT plans 1 and 2, the cases 1 (*i.e.* same trend than external price) and 3 (*i.e.* opposite trend than external price) are more often chosen while for LT plan 3, the case 4 (*i.e.* trend inversely proportional to the internal generation) is also more chosen. These new decisions allow not to have drastically changes in the gains and losses of all stakeholders.

Simulation with high constant price: If the constant price is set to the maximum inside price, the observations are completely opposite. Indeed, this new price is almost always chosen for all the LT plans. That means that for the LT plan 1, this new value is even more preferred and that for the LT plan 2, this value is an intermediate one between the old trends 1 and 2. However, for those two plans, we can observe a slight decrease of the gains of the companies compared to the previous simulations.

s	$\%_{\eta_s}$	SCR [%]
MGEM	-1.300	NA
c=1	-24.78	56.25
c=2	-29.22	97.09
c=3	-27.26	57.12
c=4	-67.37	81.36
c=5	-21.49	80.15
c=6	-90.07	68.31
c=7	-19.49	71.18
c=8	-37.08	47.50
c=9	-68.84	73.32

Table 5.68 – LT plan 1 with low constant price - Gains/losses percentages and SCRs.

1	2	3	4
64.41	0	32.49	3.10

Table 5.69 – LT plan 1 with low constant price - Daily pricing trends [%].

TIC [kW]	REP [%]	IEP [%]	PP [%]	SP [%]
4699	49.01	70.23	85.08	14.92

Table 5.70 – LT plan 1 with low constant price - Metrics analysis.

s	$\%_{\eta_s}$	SCR [%]
MGEM	+7.64	NA
c=1	-24.48	57.63
c=2	-27.75	97.46
c=3	-27.17	58.59
c=4	-58.76	83.16
c=5	-20.36	80.73
c=6	-87.84	69.56
c=7	-18.40	74.46
c=8	-36.18	50.09
c=9	-63.24	73.39

Table 5.71 – LT plan 2 with low constant price - Gains/losses percentages and SCRs.

1	2	3	4
67.11	0	32.71	0.18

Table 5.72 – LT plan 2 with low constant price - Daily pricing trends [%].

TIC [kW]	REP [%]	IEP [%]	PP [%]	SP [%]
4699	46.78	68.33	86.54	13.46

Table 5.73 – LT plan 2 with low constant price - Metrics analysis.

s	$\%_{\eta_s}$	SCR [%]
MGEM	+9.40	NA
c=1	-25.69	59.24
c=2	-29.93	96.92
c=3	-27.98	59.47
c=4	-55.52	83.77
c=5	-22.36	81.51
c=6	-89.24	68.06
c=7	-20.69	76.03
c=8	-36.12	50.99
c=9	-52.04	75.08

Table 5.74 – LT plan 3 with low constant price - Gains/losses percentages and SCRs.

1	2	3	4
50.98	0	21.94	27.07

Table 5.75 – LT plan 3 with low constant price - Daily pricing trends [%].

TIC [kW]	REP [%]	IEP [%]	PP [%]	SP [%]
4699	67.70	86.81	13.19	54.34

Table 5.76 – LT plan 3 with low constant price - Metrics analysis.

s	$\%_{\eta_s}$	SCR [%]
MGEM	+5.21	NA
c=1	-22.30	53.35
c=2	-26.25	97.73
c=3	-24.56	54.39
c=4	-57.77	86.94
c=5	-17.29	78.40
c=6	-94.29	70.36
c=7	-15.00	69.54
c=8	-37.81	44.00
c=9	-75.86	74.64

Table 5.77 – LT plan 1 with high constant price - Gains/losses percentages and SCRs.

1	2	3	4
0	99.96	0.04	0

Table 5.78 – LT plan 1 with high constant price - Daily pricing trends [%].

TIC [kW]	REP [%]	IEP [%]	PP [%]	SP [%]
4699	46.27	68.38	87.21	12.79

Table 5.79 – LT plan 1 with high constant price - Metrics analysis.

s	$\%_{\eta_s}$	SCR [%]
MGEM	+13.34	NA
c=1	-22.76	60.96
c=2	-24.79	97.17
c=3	-24.45	61.13
c=4	-54.53	83.71
c=5	-16.31	82.35
c=6	-92.23	68.62
c=7	-13.90	77.93
c=8	-37.96	52.21
c=9	-63.68	72.08

Table 5.80 – LT plan 2 with high constant price - Gains/losses percentages and SCRs.

1	2	3	4
0	99.95	0.044	0.006

Table 5.81 – LT plan 2 with high constant price - Daily pricing trends [%].

TIC [kW]	REP [%]	IEP [%]	PP [%]	SP [%]
4699	46.42	68.09	86.71	13.29

Table 5.82 – LT plan 2 with high constant price - Metrics analysis.

s	$\%_{\eta_s}$	SCR [%]
MGEM	+0.21	NA
c=1	-25.92	55.66
c=2	-29.18	97.04
c=3	-27.85	56.80
c=4	-67.43	79.40
c=5	-21.28	79.91
c=6	-90.78	68.25
c=7	-19.74	70.81
c=8	-37.83	46.95
c=9	-64.43	73.84

Table 5.83 – LT plan 3 with high constant price - Gains/losses percentages and SCRs.

1	2	3	4
0.011	96.88	0.059	3.05

Table 5.84 – LT plan 3 with high constant price - Daily pricing trends [%].

TIC [kW]	REP [%]	IEP [%]	PP [%]	SP [%]
4699	50.42	69.68	84.09	15.91

Table 5.85 – LT plan 3 with high constant price - Metrics analysis.

Lower WT generation profile

The generation profiles used as input of the tool may also have their influence on the LT decisions of investments. Given the previous simulations with unlimited investments, the WT investment has appeared to be very profitable. As the wind is intermittent and with different possible intensities over 1 year, the **LT plan 1 Ψ_1 with unlimited investments has been run again two times: once with a WT generation slightly reduced of one third and once with the WT generation divided by two**.

Simulation with WT generation slightly decreased: the LT node 9 is conserved with this new simulation. However, the percentages of savings of the companies are reduced (which makes sense given that there is less generation inside the IMG). The SCRs are increased as the REP is very close to 1.

s	$\%_{\eta_s}$	SCR [%]
MGEM	-13.31	NA
c=1	-21.24	NA
c=2	-31.94	67.77
c=3	-21.85	NA
c=4	-89.05	57.28
c=5	-18.05	NA
c=6	-228	32.14
c=7	-18.26	NA
c=8	-19.47	34.11
c=9	-97.02	51.00

Table 5.86 – LT plan 1 Ψ_1 unlimited with WT generation slightly decreased - $\%_{\eta_s}$ and SCRs.

1	2	3	4
11.17	85.35	3.27	0.21

Table 5.87 – LT plan 1 Ψ_1 unlimited with WT generation slightly decreased - Daily pricing trends [%].

TIC [kW]	REP [%]	IEP [%]	PP [%]	SP [%]
12429	99.85	87.32	59.40	40.60

Table 5.88 – LT plan 1 Ψ_1 unlimited with WT generation slightly decreased - Metrics analysis.

Simulation with WT generation divided by 2: this simulation leads to a change of LT equilibrium. Indeed, it is now the LT node 18 instead of the LT node 9.

This result means that, with this level of WT generation, it remains interesting for the WT investors to invest is such installations but, regarding the IMG as a whole, an additional generation installation is required, *i.e.* a PV installation. Note that the SCRs are increased again but the percentages of savings are even lower than with the previous simulation.

We can conclude that the intensity of the generation has its importance in the decision making process and on the percentages of savings of the investor companies. For a real IMG to be established, it will be therefore a key factor to model in the most realistic way the WT generation profile in the geographical area considered.

s	$\%_{\eta_s}$	SCR [%]
MGEM	-12.52	NA
c=1	-14.99	49.77
c=2	-17.28	71.24
c=3	-22.15	47.51
c=4	-46.95	68.16
c=5	-14.55	67.01
c=6	-50.79	43.42
c=7	-14.59	64.13
c=8	-7.51	30.11
c=9	-41.86	61.54

Table 5.89 – LT plan 1 Ψ_1 unlimited with WT generation divided by 2 - $\%_{\eta_s}$ and SCRs.

1	2	3	4
14.10	81.00	4.25	0.66

Table 5.90 – LT plan 1 Ψ_1 unlimited with WT generation divided by 2 - Daily pricing trends [%].

TIC [kW]	REP [%]	IEP [%]	PP [%]	SP [%]
13531	84.22	82.00	65.81	34.19

Table 5.91 – LT plan 1 Ψ_1 unlimited with WT generation divided by 2 - Metrics analysis.

5.8 Application to a typical IMG of nine companies with the IEO as MGEM

Objective: change the role of MGEM in order to see the impact on the DSO benefits or savings. Run the entire tool for the 3 LT pricing plans with limited investment (LT plan 1, LT plan 2 and LT plan 3) according to the 9 scenarios (Ψ_1 to Ψ_9) and with IEO as MGEM.

The previously presented microgrid is kept unchanged but the IEO is now taken into account as the MGEM. Concretely, it means that all the inside fees are now the incomes of the IEO while the DSO only receives the compensation fee of the IMG as well as his incomes linked to the exchanges with the distribution grid.

All the scenarios have been simulated according to the three LT plans with limited and unlimited investments in order to evaluate the impacts of the latter on the losses of the DSO and the benefits of the IEO/MGEM. From the management point of view, this new MGEM does not affect drastically the concept of the IMG. It just means that this is now the IEO that has the authorisations for using the data and gives advices, while the DSO is considered as any other stakeholder, without any privilege related to the IMG management.

LT plan 1 with limited investments

Tab. 5.92 shows the cash-flows of the IEO for the LT plan 1. These are computed with the incomes from the mean daily cash-flows over the 20 years of planning (as the ones of the other stakeholders).

Their values seem quite logical: the higher cash-flow values always occur with an increase of the prices (Ψ_2 if the loads remain constant, Ψ_5 if the loads increase and Ψ_8 if the loads decrease). The lowest values occur, at the opposite, when the prices decreases (Ψ_3, Ψ_6 and Ψ_9). Note that an increase of the loads inside the IMG (Ψ_4 to Ψ_6) does not lead to a drastically increase of the

IEO incomes because the exchanges inside the IMG are decreased and the SCRs are increased. With a decrease of the load (Ψ_7 to Ψ_9), the fees linked to the peak and to the exchanges inside the IMG are also decreased.

The remaining of the results are gathered in Tab. 5.95 - 5.100. The gains for the companies and the parameters of analysis are, as expected, similar to the ones with the DSO as MGEM.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
IEO/MGEM	323.17	373.50	273.59	359.18	439.17	299.79	324.62	388.46	277.71

Table 5.92 – LT plan 1 - IEO cash-flows [k€].

LT plan 2 with limited investments

For the LT plan 2, regarding the IEO cash-flow values, exactly the same trend as for the LT plan 1 can be observed, with the same order of magnitudes of the values (see Tab. 5.93). Indeed, the changes in the pricing mainly concern the DSO, for which a decrease of the losses can be observed in Tab. 5.102. However, the impact is still limited thanks to the daily pricing decisions (see Tab. 5.103). The metrics (Tab. 5.104 and 5.105) and the SCRs (5.106) are similar to those obtained for the LT plan 2 with the DSO as MGEM.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
IEO/MGEM	322.34	397.23	276.31	369.82	434.04	299.79	332.19	393.83	280.45

Table 5.93 – LT plan 2 - IEO cash-flows [k€].

LT plan 3 with limited investments

For the LT plan 3, always the same trend of the IEO cash-flow values can be observed in Tab. 5.94 but this time, their level of magnitude is impacted by the new LT pricing. Indeed, in this LT plan, the ratio defining the MGEM fee is decreased from 0.15 for the other LT plans to 0.05. For the DSO, the losses are in the same order of magnitude than for LT plan 1 (see Tab. 5.108). Again, the remaining parameters (Tab. 5.109 - 5.112) are similar to those obtained for the LT plan 3 with the DSO as MGEM.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
IEO/MGEM	200.72	243.59	177.92	235.41	276.87	195.58	202.81	249.45	174.42

Table 5.94 – LT plan 3 - IEO cash-flows [k€].

LT plans with unlimited investments

The results for the unlimited investments with the IEO as MGEM are shown in the Appendix E. The observations are globally the same, except that the losses for the DSO are obviously more important (around 30%).

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
Eq.	27	27	27	27	27	27	27	27	27
$\sum I_{simu,d}$	17491	27017	18871	99292	89858	89066	93703	104746	81721

Table 5.95 – LT plan 1 with IEO - Equilibrium and number of simulated days analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
DSO	-12.0	-13.0	-9.40	+1.06	-11.8	-14.1	-6.93	-4.24	-12.3
c=1	-25.3	-27.5	-22.4	-23.1	-24.5	-22.5	-30.0	-31.8	-28.2
c=2	-29.3	-29.2	-27.8	-25.8	-29.5	-26.4	-34.8	-35.2	-34.3
c=3	-27.9	-29.1	-24.9	-26.1	-27.6	-25.3	-31.9	-34.1	-30.2
c=4	-69.8	-63.2	-66.3	-62.1	-61.8	-73.8	-65.3	-60.9	-66.6
c=5	-21.5	-22.5	-19.1	-19.3	-20.5	-19.0	-24.8	-26.3	-23.6
c=6	-91.0	-78.5	-105	-68.3	-59.8	-80.5	-134	-112	-166
c=7	-19.6	-19.9	-17.3	-17.2	-18.5	-17.0	-22.4	-23.8	-21.5
c=8	-37.4	-39.5	-33.6	-34.5	-35.6	-33.6	-45.2	-47.3	-42.3
c=9	-71.9	-68.0	-71.4	-57.5	-77.2	-83.7	-61.4	-51.9	-88.9

Table 5.96 – LT plan 1 with IEO - Gains/losses analysis for each scenario [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
1	20.32	20.49	19.86	21.32	20.21	20.54	19.86	19.84	19.20
2	73.77	72.81	73.66	71.68	73.04	72.29	74.30	74.22	74.87
3	5.87	6.69	6.47	6.98	6.74	7.15	5.76	6.03	5.85
4	0.04	0.01	0.01	0.02	0.01	0.02	0.08	0.07	0.08

Table 5.97 – LT plan 1 with IEO - Daily pricing percentages [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
TIC [kW]	4699	4699	4699	4699	4699	4699	4699	4699	4699
REP [%]	51.89	50.19	48.26	45.83	46.44	47.48	52.85	52.42	53.71
IEP [%]	69.35	68.84	68.74	65.05	66.23	65.05	71.82	71.93	71.83

Table 5.98 – LT plan 1 with IEO - Internal exchanges analysis.

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
PP [%]	83.17	85.00	85.64	87.30	87.05	86.02	82.25	82.56	81.67
SP [%]	16.83	15.00	14.36	12.70	12.95	13.98	17.75	17.44	18.33

Table 5.99 – LT plan 1 with IEO - External exchanges analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
c=1	59.49	55.27	59.67	60.13	60.52	64.79	58.63	58.16	60.10
c=2	96.74	96.69	96.60	98.52	98.48	98.09	92.41	92.73	92.60
c=3	59.71	56.82	60.23	62.03	62.54	66.19	56.61	56.57	58.08
c=4	76.99	83.38	82.80	82.43	83.21	80.04	79.18	79.39	78.76
c=5	81.87	79.65	81.84	85.48	85.61	87.70	76.31	76.11	77.22
c=6	67.32	66.60	66.73	74.37	73.92	72.10	58.27	58.37	58.34
c=7	73.61	73.12	75.81	73.69	74.55	77.99	74.06	74.08	75.94
c=8	50.69	47.70	51.49	50.52	51.13	55.27	50.71	50.66	52.69
c=9	74.23	73.58	72.93	74.95	70.62	72.91	72.87	71.94	69.10

Table 5.100 – LT plan 1 with IEO - Self-consumption rates [%].

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
Eq.	27	27	27	27	27	27	27	27	27
$\sum I_{simu,d}$	16490	14967	15817	93499	85167	84809	100049	93742	93942

Table 5.101 – LT plan 2 with IEO - Equilibrium and number of simulated days analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
DSO	-8.67	-9.20	-8.06	-0.97	-16.3	-5.67	-14.5	-11.8	-8.64
c=1	-23.9	-26.2	-22.4	-22.0	-24.0	-21.7	-29.7	-31.5	-27.4
c=2	-27.6	-28.5	-27.3	-24.9	-25.2	-25.3	-34.3	-34.7	-33.8
c=3	-26.0	-28.7	-24.3	-25.2	-26.8	-24.6	-31.9	-33.9	-29.6
c=4	-59.7	-56.2	-63.1	-59.5	-67.9	-67.7	-69.3	-62.7	-66.2
c=5	-19.6	-21.4	-18.2	-18.3	-19.4	-17.9	-24.2	-25.7	-22.6
c=6	-88.8	-79.1	-108	-67.4	-60.4	-79.5	-136	-114	-169
c=7	-17.5	-19.0	-16.1	-16.1	-17.3	-16.0	-21.7	-23.2	-20.2
c=8	-36.5	-39.3	-34.6	-34.0	-35.9	-33.2	-45.5	-47.9	-42.9
c=9	-75.8	-72.6	-71.2	-68.3	-76.0	-87.1	-74.3	-69.5	-79.2

Table 5.102 – LT plan 2 with IEO - Gains/losses analysis for each scenario [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
1	41.96	41.95	41.40	40.93	41.96	41.62	40.78	41.44	40.75
2	42.86	43.76	43.62	42.94	42.45	42.93	44.97	44.25	44.97
3	15.17	14.28	14.98	16.11	15.57	15.43	14.21	14.24	14.22
4	0.01	0.01	0.00	0.02	0.02	0.02	0.04	0.07	0.06

Table 5.103 – LT plan 2 with IEO - Daily pricing percentages [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
TIC [kW]	4699	4699	4699	4699	4699	4699	4699	4699	4699
REP [%]	47.33	48.27	46.55	44.82	46.45	46.85	52.99	52.51	52.49
IEP [%]	67.70	67.96	67.39	64.76	65.19	65.47	72.05	71.50	72.45

Table 5.104 – LT plan 2 with IEO - Internal exchanges analysis.

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
PP [%]	86.42	85.25	86.78	87.87	86.71	86.57	81.90	82.45	82.34
SP [%]	13.58	14.75	13.22	12.13	13.29	13.43	18.10	17.55	17.66

Table 5.105 – LT plan 2 with IEO - External exchanges analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
c=1	57.28	60.99	60.89	63.63	60.79	61.32	60.14	59.69	59.08
c=2	97.59	97.00	96.96	98.41	98.42	98.30	92.18	93.05	91.81
c=3	58.14	61.40	60.95	65.23	62.62	63.22	58.03	57.37	57.09
c=4	85.02	81.08	83.96	82.54	82.29	82.06	77.69	78.25	79.10
c=5	80.60	82.46	82.34	87.42	85.74	86.46	77.00	76.57	76.28
c=6	69.64	68.05	67.98	74.02	74.03	73.35	57.62	59.56	56.62
c=7	73.93	76.95	77.52	77.32	73.86	74.98	76.143	75.43	75.22
c=8	48.90	53.28	52.17	54.34	51.09	51.57	52.95	52.38	51.27
c=9	73.13	72.42	74.65	74.02	73.61	71.18	71.69	72.68	70.37

Table 5.106 – LT plan 2 with IEO - Self-consumption rates [%].

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
Eq.	27	27	27	27	27	27	27	27	27
$\sum I_{simu,d}$	16668	20020	13939	103989	86248	83772	98531	100846	98245

Table 5.107 – LT plan 3 with IEO - Equilibrium and number of simulated days analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
DSO	-12.4	-11.7	-10.1	-7.23	-6.33	-10.3	-7.13	-8.33	-15.3
c=1	-25.7	-27.7	-24.1	-24.0	-25.4	-23.2	-31.3	-32.3	-28.7
c=2	-29.7	-30.2	-29.5	-26.6	-26.7	-26.5	-35.3	-35.3	-34.4
c=3	-28.0	-30.4	-26.5	-27.2	-29.1	-26.1	-33.4	-34.8	-30.9
c=4	-65.7	-63.9	-66.3	-61.8	-64.9	-68.3	-61.0	-54.1	-67.5
c=5	-21.7	-23.4	-20.6	-20.3	-21.6	-19.6	-26.0	-26.8	-24.2
c=6	-91.8	-79.0	-111	-69.7	-61.4	-80.5	-134	-113	-161
c=7	-19.8	-21.5	-18.9	-18.5	-19.8	-17.8	-23.7	-24.5	-22.3
c=8	-37.8	-40.0	-36.0	-35.2	-37.0	-34.0	-46.1	-48.1	-42.4
c=9	-76.4	-67.8	-72.9	-73.7	-65.0	-81.0	-73.7	-68.2	-84.9

Table 5.108 – LT plan 3 with IEO - Gains/losses analysis for each scenario [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
1	0.28	0.29	0.22	0.29	0.32	0.32	0.25	0.23	0.23
2	99.44	99.43	99.51	99.42	99.37	99.35	99.44	99.44	99.41
3	0.25	0.23	0.25	0.27	0.29	0.30	0.22	0.24	0.26
4	0.03	0.05	0.02	0.02	0.02	0.03	0.09	0.09	0.10

Table 5.109 – LT plan 3 with IEO - Daily pricing percentages [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
TIC [kW]	4699	4699	4699	4699	4699	4699	4699	4699	4699
REP [%]	49.86	51.88	47.44	45.59	47.14	44.56	53.69	50.93	52.41
IEP [%]	68.53	69.52	68.40	65.87	65.28	64.95	72.01	71.96	71.48

Table 5.110 – LT plan 3 with IEO - Internal exchanges analysis.

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
PP [%]	84.92	83.13	86.23	87.38	86.46	87.79	81.66	83.28	82.21
SP [%]	15.08	16.87	13.77	12.62	13.54	12.21	18.34	16.72	17.79

Table 5.111 – LT plan 3 with IEO - External exchanges analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
c=1	59.89	60.85	60.07	60.05	62.71	61.92	59.59	58.97	59.58
c=2	96.96	96.60	96.94	98.53	98.34	98.28	92.21	92.46	92.65
c=3	59.84	61.09	60.35	62.06	64.53	63.48	57.51	57.17	57.43
c=4	82.75	76.02	81.22	82.71	81.02	83.98	77.83	80.52	79.07
c=5	81.87	82.43	82.17	85.49	86.91	86.02	76.50	76.45	76.80
c=6	68.14	66.65	67.88	74.27	73.71	73.28	57.35	57.76	58.89
c=7	74.45	75.42	76.04	74.41	76.68	75.97	75.43	75.45	75.07
c=8	51.60	52.75	52.45	51.06	53.33	52.55	52.21	51.25	52.41
c=9	71.21	73.23	75.92	73.31	71.93	73.07	72.62	72.27	70.89

Table 5.112 – LT plan 3 with IEO - Self-consumption rates [%].

5.9 IMG management advices: conclusions

The developed planning tool for IMGs can be used in two ways: the first one is dedicated to an overall study of the possibility to shift from a classical industrial estate to an IMG and the second one is dedicated to a specific study of an IMG layout.

For the first one, many parameters and information have to be provided by the companies to the foreseen MGEM in order to run the tool. Therefore, the first step is to properly and contractually define the agreements between them for sharing all the confidential information. The main information that the companies have to give to the MGEM are: their load profile, their maximum investment budget, their available area, their possibilities of doing LM and their current electricity bill. In addition, the MGEM has to manage the price and generation profiles (PV and WT) for the considered industrial area.

To provide an analysis as complete as possible of the IMG possibilities, the MGEM has also to handle the uncertainty linked to the LT evolution of the load and price profiles inside the IMG. It is why the tool can be run according to 9 scenarios, combining the increase, the decrease and the steadiness of those profiles. The MGEM can choose to run all or only part of them.

The next crucial point that has to be considered is the LT pricing applied inside the IMG. Currently, it is probably one of the most complex and delicate aspect of the tool. Indeed, as the current regulatory framework is kept only for the external exchanges and completely neglected for the internal exchanges, the role of the MGEM could be to define the pricing trend inside the IMG. For that purpose, the tool allows to consider four pricing schemes inside the IMG that are: the same trend than the outside price, a constant price, the opposite trend than the outside price and a price profile which is inversely proportional to the amount of generation inside the IMG. These considerations allow the MGEM to have guidelines regarding the fairer pricing choice to be adopted inside the IMG, thanks to the use of game theory for each day.

If the MGEM wants to perform a complete analysis of the IMG, all those elements have to be adapted and tested to provide global simulation results. Otherwise, if the goal is only to test a configuration of the potentially already existing IMG, a unique simulation can be run with the mentioned parameters already fixed.

In order to go further in the IMG analysis, some investigations can also be conducted regarding LM, the sharing of investments and the ESS. However, in the current version of the tool, those simulations are still time consuming and because of that, they are sometimes considered in a quite simple way to be handled. It can therefore be applied for a fixed configuration of the tool to only provide additional trends.

In this work, a complete analysis of an IMG composed of 9 companies with various load profiles plus the DSO has been realised. The 9 scenarios have been simulated according to 6 LT plans: 3 LT pricing plans with both limited and unlimited investment possibilities. The LT pricing plans were a middle one, a DSO boost one and a IMG boost one.

Of course, lots of information that the companies have to provide have been set randomly (in a realistic way though) to be relevant for the analysis.

The different simulations have shown the benefit of the IMG concept for all the companies. With limited investments, all of them should invest in the well sized installations (PV and/or WT) for them, *i.e*. the LT equilibrium is the node 27. With unlimited investments, according to the considered scenarios, the decision to not or partly invest in PV is often taken (mainly when the prices and/or the load decreases), *i.e*. the LT equilibrium is the node 9 or 18.

Both approaches (with limited and unlimited investments) are relevant but result in different considerations of the IMG:

- With limited investment, the investments seem fair and appropriate for all the stakeholders. The self-consumption inside the IMG is relatively high, making it less dependent from the point of view of the main grid. The DSO losses are, in the worst cases, of around maximum 10% as shown for the three first plans illustrated in Fig. 5.19. The penetration of RES in the IMG is realistic;
- With unlimited investments, the investment budget seems unrealistic without any aids. Moreover, when the LT node 9 or 18 is the LT equilibrium, the investors companies are, over 20 years making huge benefits at the expense of mainly the DSO, as illustrated for the three last plans in Fig. 5.19. Indeed, his losses are increased until around 30% for several scenarios. The total of RES installations is almost three times higher than the IMG current load peak. Therefore, the self-consumption rates inside the IMG are quite low (under 50%) while the selling probability to the main grid is higher than 50%. Therefore, such investments could be perceived differently from the point of view of the distribution network, in order to provide services to the suppliers and/or the DSO and regarding the distribution of the costs and the benefits.

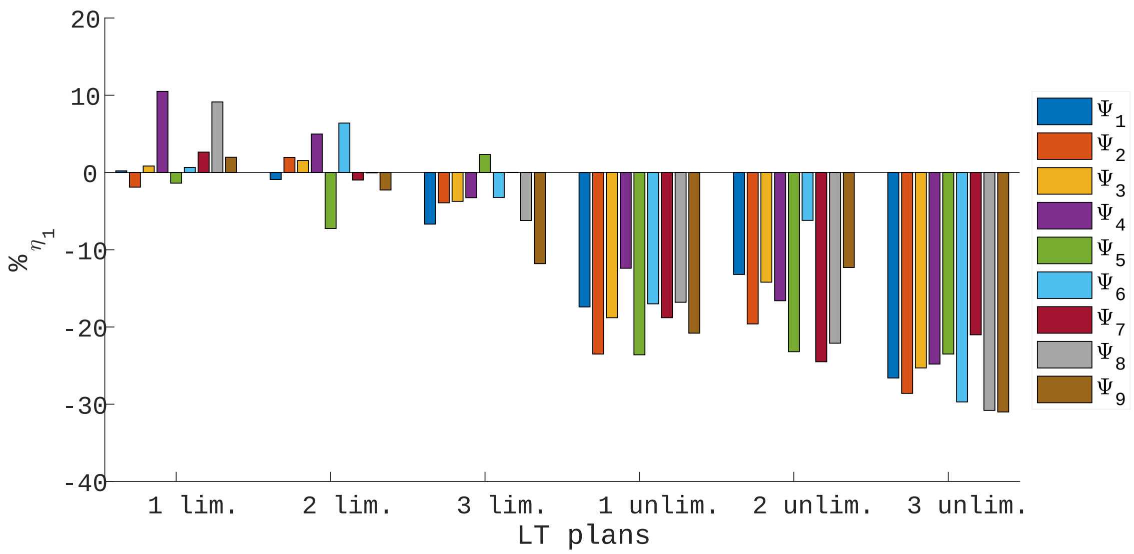


Figure 5.19 – Percentages of gains or losses of the DSO as MGEM.

For the interested reader, a summary of the percentages of benefits of the companies is presented in the Appendix F with the same kind of figures as Fig. 5.19.

The tool has deliberately been run completely each time in order to observe its robustness. For equivalent profiles evolutions, the obtained self-consumption rates vary within a maximum range of 5%, which testifies to the accuracy of the results. Moreover, comparing the percentages of gains and losses of the companies between the simulations with the DSO or the IEO as MGEM, their variation is only about maximum 2% for the companies of class 2 and a few percent for those of class 1 (which have more unstable profiles to predict).

In all simulations, the ST game application has demonstrated its effectiveness and is relevant to justify the IMG behaviour in a fair way. Indeed, the daily pricing repartition is adapted according to the LT pricing plan (DSO boost or IMG boost) to not *over-boost* the DSO or the companies respectively.

For this study case, the different investigations have been performed to measure their impact on specific configurations of the IMG. Regarding the LM, it allows a small increase of the self-consumption rates and of the cash-flows over 1 year for the companies that are performing LM. However, given that the tool advices to apply it most of the time, the benefit seems quite low, particularly because LM is here considered as totally free of charge for the companies but could in reality lead to a small cost for them.

The concepts of joint and associated investments have also been approved for this IMG. The benefit is such that, for the LT plan 1 with unlimited investments, the LT equilibrium node is changed and allows more investments.

Finally, the benefit of an ESS has been demonstrated based on the self-consumption rates analysis but the considered cost was still to high to allow a change of decision and to consider such a shared investment. However, the cost of ESS could be adapted according to the battery market over the years to evaluate from which price it becomes profitable. However, for that purpose, a more accurate study of the current prices over the ESSs industry should be performed (with a prediction for the future years).

All along the results observation, some key factors have been defined and tested in order to see their influence on the decision making process. The load peak pricing scheme has mainly impacted the percentages of savings/losses of the MGEM. The daily constant prices variations has led to different pricing choice distributions resulting from the ST game. Finally, the variation of the intensity of the WT generation profile has shown the importance of using the most accurate profiles as possible in the considered area.

In order to assess the influence of the role of MGEM on the DSO benefits, the same IMG has also been simulated according to the 6 LT plans and the 9 scenarios with the IEO as MGEM. The percentages of gains/losses are shown in Fig. 5.20 and the cash-flows of the IEO are gathered in Fig. 5.21. Of course, the DSO has almost always a negative percentage, which means that, when he does not perceive the fees for the MGEM roles, he is not making benefits with the IMG, even with the limited investments cases. The losses are even increased until almost 40% for some scenarios.

Regarding the IEO, its benefits are quite the same for the LT plans 1 and 2, but decrease with the third scenario, given that fee of the MGEM is reduced to favour the companies inside the IMG with this LT pricing plan. Note that, thanks to its benefits, the IEO could become an investor inside the IMG in order to provide more internal generation and/or to give aids for the RESs and ESS investments.

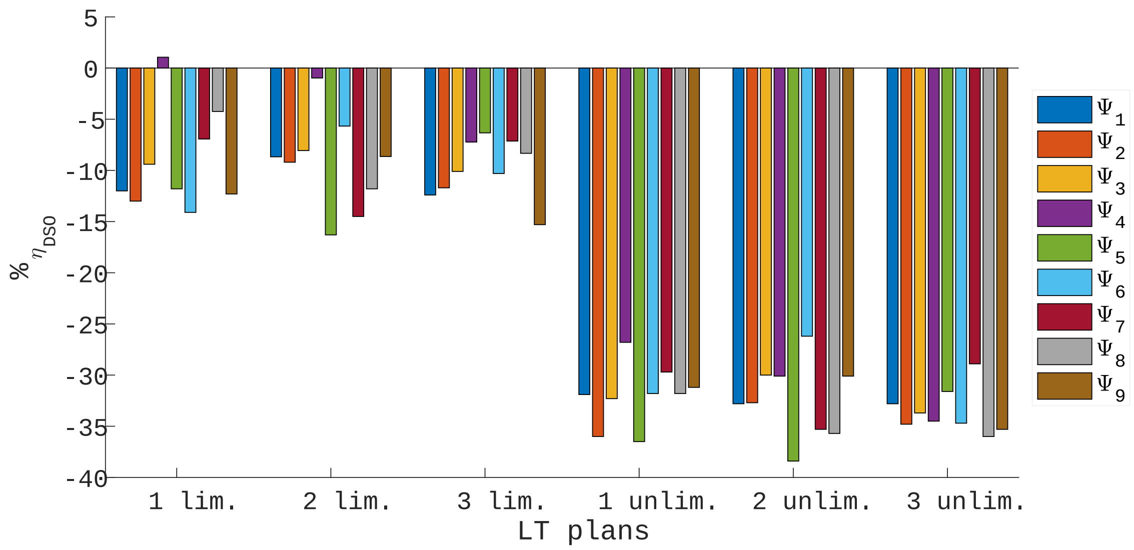


Figure 5.20 – Percentages of gains or losses of the DSO with the IEO as MGEM.

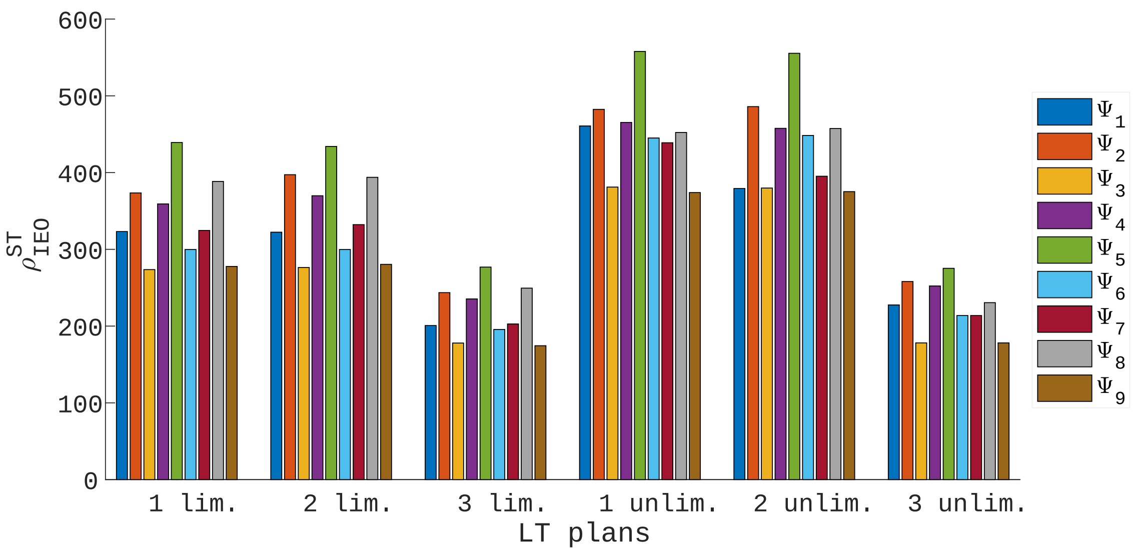


Figure 5.21 – Cash-flows of the IEO as MGEM

All the conducted simulations have validated the developed methodology as well as its robustness. The test case has permitted to evaluate all the possibilities of our tool. However, given the huge number of parameters to be adapted according to the wishes of the DSO, the companies, the IEO and the MGEM, many other simulations could be performed and discussed.

Conclusion and perspectives

This thesis falls within the context of energy transition that is getting more and more attention since several years. The main goal of this energy transition is to ensure a decarbonisation and denuclearisation of the generation fleet to advance towards a greener and safer new one. In this context, recent years have witnessed a change of paradigm of the electrical system. In order to manage the stress linked the decentralised and intermittent generation systems, the latter has to become smart, with active stakeholders. In addition, a way to facilitate the integration of RESs and ESSs is to establish a microgrid framework, well managed and less dependent of the main network.

This thesis focused on two main points regarding such microgrids in the industrial sphere: the establishment of a new regulatory framework inside the IMG and the development of a tractable and reliable long-term planning tool for IMGs, including all the stakeholders. For that purpose, the main original contributions of this thesis are:

- The establishment of a new internal regulatory framework and pricing scheme making attractive the participation to an IMG;
- The setting up of an energy management procedure including internal and external (with the DN) exchanges, managed by a properly defined MGEM;
- The application of game theory to consider all the stakeholders including the MGEM;
- The development of a two time horizons solving methodology, which includes both long and short-term decisions. This has been realised through looped extensive games;
- The implementation of a methodology allowing the generation of typical days while ensuring the convergence of the tool results via a stratified Monte Carlo sampling procedure;
- The integration of a LM procedure as well as the possibility of considering a shared ESS in the short-term energy management;
- A distribution methodology among the companies for the shared investments;
- The consideration of two different entities as MGEM: the DSO and the IEO.

Regarding **the regulatory framework**, the existing one forbids the direct exchanges between companies and the prevailing electricity prices are ruled by an inescapable energy market. Therefore, in order to develop a microgrid structure, some financial incentives have to be proposed to the participating companies. For that purpose, an attractive new pricing scheme allowing new kinds of exchanges has been set up inside the IMG, leading to a particular IMG regulatory framework. On this basis, a proper short-term energy management of the IMG has been established and validated. In parallel, the role and the functions of the MGEM have been clearly defined.

For **the decisions making process**, the main issue was to find a way to consider all the stakeholders (including the MGEM and the DSO) on equal terms with their respective objectives, which can be different or even conflicting. For that purpose, a decision making process using game theory has been implemented. To that end, extensive games have been used twice: on the one hand at a long-term time horizon for the investments decisions by the companies and, on the other hand each day to make the daily IMG price choice by the MGEM.

From the new IMG framework and this concept of looped games, a first tool (simulating 7300 days) has been developed and tested on a small IMG, only including the DSO and three companies with two possible investment decisions, namely PV and ESS installations for the companies and low or medium pricing for the MGEM. This first tool has given promising results regarding the increase of the companies NPVs and therefore the decrease of the times of return on investments. The possibility of performing LM each day for some companies has also been considered. However, this tool was time consuming and, given that the size of the games are increasing exponentially with the number of stakeholders and decisions, the consideration of larger IMGs would not have been tractable in this initial version of the tool.

Therefore, the second part of the work has been devoted to **make the tool tractable for larger IMGs**. For that purpose, different approaches have been explored, including other kinds of games or new methodologies for solving games as well as data clustering. The final choice made was to **generate typical days through a monovariate and stratified Monte Carlo sampling**. Each day of the week is therefore characterised by mean cash-flows for every stakeholders, to be extended over the planning horizon.

In addition, **the LT game organisation has be adapted** in order to form communities of investors according to the PV and/or WT investments. Moreover, **the LM operation has been extracted from the core of the tool** in order to be applied on a yearly basis (which makes more sense given the uncertainty of the load evolution over 20 years).

This new version of the tool has been applied to an IMG composed of 9 companies plus the DSO. The tool was run according to 3 LT pricing plans (an average one, a DSO boost one and an IMG boost one), with both limited and unlimited amounts of investments (*i.e.* 6 LT plans in total). Moreover, each LT plan was simulated according to 9 scenarios of evolution of the load and price profiles.

The results of the simulations have been thoroughly analysed in chapter 5. Mainly, it can be concluded that the IMG concept is interesting for the companies, the DSO and the IEO. For the companies, the benefits linked to the investments are increased thanks to the IMG. Moreover, inside the IMG, the energy management is performed by the MGEM, which is easier for them. Regarding the DSO, the potential losses that would occur if the companies were only investing (without the IMG structure) are decreased in all cases or even changed in benefits when the DSO is the MGEM. In order to discuss the benefits linked to the role of MGEM, the IEO has been considered as MGEM for some simulations. In the latter, financial losses have been observed for the DSO while the IEO makes benefits, which testify that the role of MGEM is advantageous. The benefits of the IEO could be invested in the IMG or used to provide financial aids to the companies to further promote the IMG concept.

The robustness of the tool has also been demonstrated. However, the results obtained depend on a large quantity of inputs and parameters that can lead to changes in the IMG behaviour. The performed simulations have notably shown the importance of the budget of the companies and the available area for their investment(s) in the IMG consideration (regarding the RES penetration and the interaction with the DN). All along the results analysis, other key elements were noticed as the type of load profiles of the companies, the appropriate generation profiles, the considered investment costs, the level of pricing as well as the load peak pricing.

Perspectives

The planning tool of IMGs developed in this thesis has addressed lots of thematics. The main challenge was to properly consider the different contributions and to associate them while keeping a tractable planning tool.This paves the way to numerous perspectives.

The main one is to **investigate further ways to reduce the computation time of the tool while increasing the accuracy of some considerations**. For example, to obtain a tractable tool in its current version, the LT game had to be adapted by considering communities of investors. However, the first idea was to keep the stakeholders independent one from each other. The researches did not lead to a feasible solution but with deeper specific mathematical research, some solutions using game theory principles might be found.

Many perspectives are related to the **LT investigations**. Indeed, they are currently considered in a restricted way because they are time consuming, even if they are implemented in a quite simple manner. Therefore the challenge remains twofold: on the one hand, considering these investigations in a more accurate way and, on the other hand, decreasing the execution time of the tool.

Regarding the LM, it is currently considered in a general way for all companies. It could be adapted to specific kinds of industrial processes while considering the raw materials and the products. Moreover, the cost linked to the application of LM could be quantified. It could lead to a more effective application of LM, in a way closer to its practical use in reality.

In the same idea, the ESS considered here is a battery without any model. First of all, the battery modelling and the optimisation of its charge and discharge could be improved. Secondly, other kinds of storage systems could be considered (other technologies of batteries, compressed air, pumped-storage, flywheel, and so on).

The consideration of EVs has not been fully exploited in the existing version of the planning tool given the limits of the current implemented procedure and its important computation time.

As these vehicles are largely promoted, the possibility of integrating an EVs fleet inside the IMG to increase the self-consumption rate of the IMG seems inescapable. Moreover, if an ESS is also present in the IMG, a daily joint optimisation could be really interesting to explore and to integrate to the daily energy management of the IMG (if it is possible regarding the simulation time).

Moreover, in the current version of the tool, a simple load-flow is performed each day after the management of the exchanges to check if there is no overvoltage and/or congestion. However, the grid is system as perfect, without any losses. When the RES (or ESS) is located just next to the company, this assumption seems well justified. However, in the case of shared investments in some available areas inside the IMG, the distance between certain companies and the shared installation can be much longer and, therefore, **the inclusion of a losses calculation** would be required.

In a broader vision, if the considered IMG is still larger, a real internal electricity market could be established. Moreover, this study only focused on the study of electricity inside the IMG. The work could be completed by integrating another energy product as the gas in the decision making process. The notion of IMG and energy exchanges would therefore include the electricity and the gas exchanges and their combination, in order to take fully advantage of them and their possible interactions. In the same idea, a heat network (*e.g.* via geothermal installation) and co-generation systems could also be considered to further extend the notion of energy to the heat. Moreover, the renovation and isolation of the companies buildings as well as new heating technologies (*e.g.* heat pumps and thermal panels) could also be taken into account into the investment decisions making process and the long-term planning tool.

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Appendix A

List of Publications

A.1 Publications related to the thesis

A.1.1 Peer-review journal article

C. Stevanoni, Z. De Grève, F. Vallée, Member, IEEE, and Olivier Deblecker, "Long-Term Planning of Connected Industrial Microgrids: A Game Theoretical Approach Including Daily Peer-to-Microgrid Exchanges", *IEEE Trans. On Smart Grid*, Vol. 10, No. 2, pp. 2245-256, March 2019.

A.1.2 Peer-review conference papers

C. Stevanoni, F. Vallée, Z. De Grève, O. Deblecker and P. Couneson, "Long-Term Planning of Industrial Microgrids", *In Proc. Young Researchers Symposium*, Eindhoven, The Netherlands, May 2016.

C. Stevanoni, F. Vallée, Z. De Grève and O. Deblecker,"On the use of game Theory to study the planning and profitability of industrial microgrids connected to the distribution network", *In Proc. 24th International Conference on Electricity Distribution (CIRED 2017)*, Glasgow, Scotland, June 2017.

C. Stevanoni, F. Vallée, Z. De Grève and O. Deblecker, "Daily Game Theoretical Management of a Connected Industrial Microgrid", *In proc. 2017 IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia)*, Auckland, New-Zealand, Dec. 2017.

C. Stevanoni, F. Vallée, Z. De Grève and O. Deblecker, "Optimized Decentralized and Centralised Load Management Techniques in Industrial Microgrids", *In proc. International Conference on Electricity Distribution (CIRED) Workshop 2018*, Ljubljana, Slovenia, June 2018.

A.2 Publications in Electrical Engineering

A.2.1 Peer-review conference papers

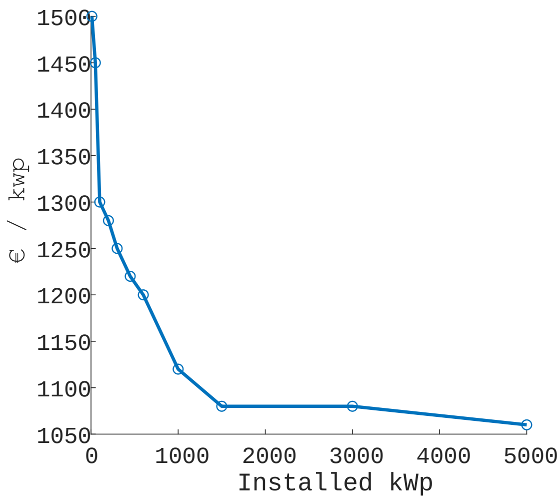
C. Stevanoni, O. Deblecker and F. Vallée, "Cooperative Control Strategy of Multifunctional Inverters For Power Quality Enhancement in Smart Microgrid", *In proc. International Conference on Renewable Energies and Power Quality (ICREPQ'16)*, Madrid, Spain, May 2016.

O. Deblecker, **C. Stevanoni**, F. Vallée, "Cooperative Control of Multi-Functional Inverters for Renewable Energy Integration and Power Quality Compensation in Micro-Grids", *In Proc. International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, Anacapri, Italy, June 2016.

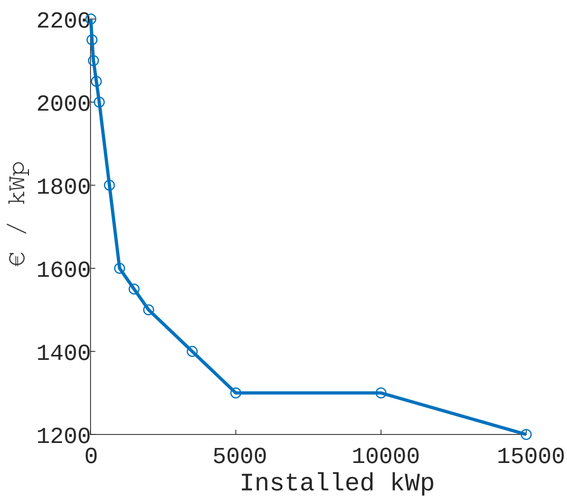
Appendix B

PV and WT investment prices

The figures B.1a and B.1b show the evolution of the PV and WT installation prices per kWp installed in function of the size of the installation. This values have been set according to the current mean costs of the PV and WT installations to our knowledge. The evolution has been established to be relevant for the simulations while realistic.



(a) PV cost evolution.



(b) WT cost evolution.

Figure B.1 – Investment costs evolution.

Appendix C

EVs fleet inside the IMG

Electric vehicles: modelling and optimisation

In the current context of the energy transition and proliferation of EVs, the inclusion of the latter in the planning tool seems inescapable. The concept developed in the tool is the following one: a unique EVs fleet is considered for the whole IMG. All the vehicles (of the workers) are contractually linked to the fleet aggregator for both the charge and discharge of the batteries. This contract allows the aggregator to know the needs of each worker, *e.g.* regarding his minimum State Of Charge (*SOC*) at the end of the day and the number of kilometers that he has to make with the vehicle between the end of one day and the beginning of the next day. The aggregator will optimise the charge of the whole fleet according to the available generation inside the IMG and to the purchasing price of electricity to the main grid. To simplify the problem, it will be considered that the fleet aggregator is the MGEM.

The EVs fleet should provide a service to the workers by ensuring the proper charge of their EV batteries while increasing the self-consumption of the generation inside the IMG. Indeed, given the pricing framework set up, it should be more interesting to sell electricity to the EVs inside the IMG than to the main grid. Moreover, if the discharge of the batteries is also considered, it should be more interesting to buy electricity from them (inside the IMG) than from the main grid. Note that if the discharge is considered, the contract between the workers and the aggregator need to be more extended. Indeed, it has to ensure that the EV batteries are only charged at work to avoid penalising the workers (by discharging electricity charged at home). Therefore, the minimal *SOC* needs to take into account at least one round-trip to home, eventually with consideration of specific wished trips.

The EVs fleet optimisation problem is only formulated to minimise its charging costs while respecting the constraints imposed by the workers. The electricity that can be used by the vehicles is the remaining of the IMG generation, after self-consumption and internal exchanges between companies (*i.e.* after the STEM in the core of the tool). At the opposite, the EV batteries can be discharged to decrease the quantity of electricity that has to be purchased to the main grid by the companies. That means that the EVs fleet is, in the same way than the ESS, an additional asset for companies.

Therefore, **the integration of the EVs is realised by two steps**, extracted from a master thesis realised in the Electrical Power Engineering Unit of the University of Mons [132]:

- the first one concerns the optimisation of the charge and discharge of the batteries of the EVs fleet;
- the second one is relative to the computation of the mean daily benefits for the IMG linked to the EVs fleet (and then the benefit of each producer company) through a Monte Carlo analysis.

Regarding the **first step**, the inputs and outputs of the optimisation problem are gathered in Fig. C.1. The optimisation problem is defined as a mixed integer linear one and its objective function is defined by C.1, for M EVs:

$$\min_{E,R,T} \sum_{i=1}^{i=M} \sum_{j=1}^{j=11} \left[E(j,i) \times \pi_{in,p,h} + R(j,i) \times \pi_{out,p,h} - T(j,i) \times \pi_{in,s,h}\right] \times plug(j,i) \tag{C.1}$$

where:

- $E(j,i)$ and $R(j,i)$ are, respectively, the energy purchased inside the IMG and via the DN by the EV i at the hour j ;
- $T(j,i)$ is the energy sold to the IMG by the EV i at the hour j

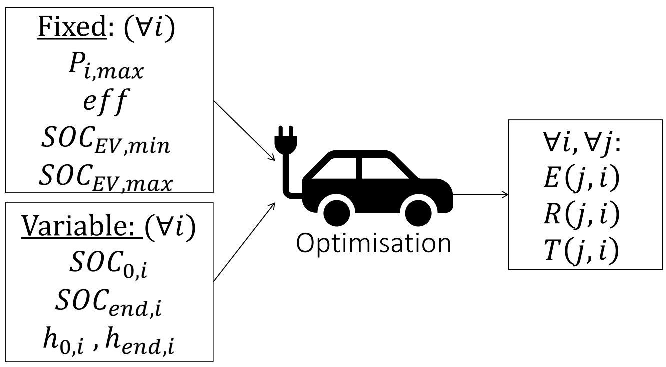


Figure C.1 – EVs optimisation: MILP inputs and outputs.

Regarding the constraints linked to the IMG, the total amount of energy purchased inside the IMG ($\sum_i E(j,i)$) can not exceed $G_{tot,j}$ and the total amount of energy discharged on the IMG ($\sum_i T(j,i)$) can not exceed $L_{tot,j}$, for each hour j.

Regarding the constraints linked to the characteristics of the EVs batteries, at each hour j, the energy exchanged for each vehicle i must be limited by the maximum power of charge and discharge of the EV battery. The power is assumed to be the same whether the battery is charged or discharged and is denoted $P_{i,max}$ and $-P_{i,max}$, respectively:

$$-P_{i,max} \leq E(j,i) + R(j,i) - T(j,i) \leq P_{i,max} \tag{C.2}$$

Moreover, the quantity of energy charged must be enough to respect the constraints imposed by the worker. If the initial state of energy of the EV i is denoted $E_{0,i}$ and the final state of energy imposed by the worker is denoted $E_{d,i}$, the following constraint must be fulfilled:

$$\sum_{j} [E(j,i) + R(j,i) - T(j,i)] \times plug(j,i) = E_{d,i} - E_{0,i} \tag{C.3}$$

After solving this optimisation problem, the amounts of energy that need to be sold or purchased to the main grid are changed for the companies. Therefore, as for the ESS, this has an impact on their daily cash-flow. However, contrary to the ESS, lots of uncertainties are linked to the EVs fleet operation, notably:

- the time of arrival ($h_{0,i}$) and departure ($h_{end,i}$) of each EV i;
- the initial $SOC_{0,i}$ of the battery of each EV i;
- the desired final $SOC_{end,i}$ specified by the workers at the hour of the departure from work.

Therefore, the goal of the **second step** in our tool is to determine how beneficial could be such a EVs fleet for the companies considered as whole inside the IMG. For that purpose, the principle presented in Fig. C.2 is applied.

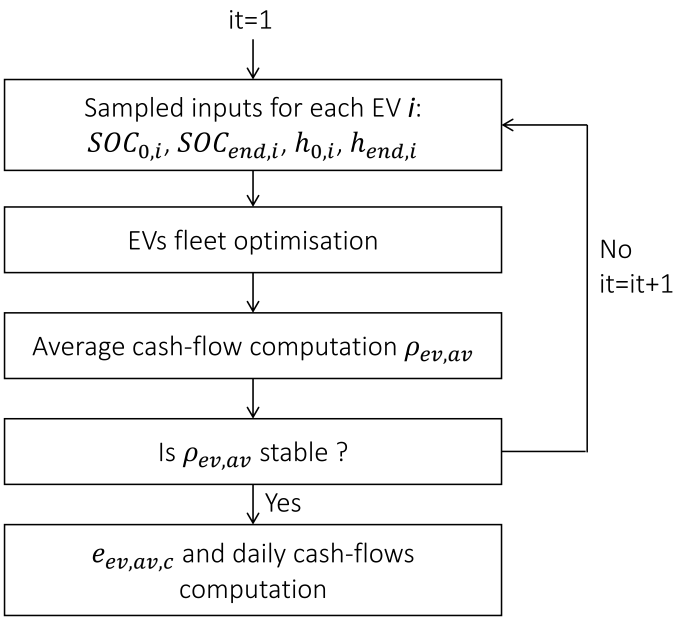


Figure C.2 – MC sampling principle for the EVs optimisation loop.

For each simulated day, the optimisation is performed a huge number of times with a MC sampling on the previously cited variables, $i.e$ the arrival and departure hours of each EV i ($h_{0,i}$ and $h_{end,i}$) as well as its initial $SOC_{0,i}$ and final $SOC_{end,i}$.

At each iteration it, a global cash-flow $\rho_{ev,it}$ is computed for the whole IMG regarding the total energy to be purchased and/or sold inside the IMG and via the DN (see C.4) as well as the average cash flow over the set of iterations (see C.7).

$$\rho_{ev,it} = \sum_{j=1}^{j=11} \left(\rho_{sale,j} - \rho_{purch,j}\right) \tag{C.4}$$

with:

$$\rho_{sale,j} = \sum_i E(j,i) \times \pi_{in,s,j} + (G_{tot,j} - \sum_i E(j,i)) \times \pi_{out,s,j} \tag{C.5}$$

$$\rho_{purch,j} = \sum_i T(j,i) \times \pi_{in,p,j} + (L_{tot,j} - \sum_i T(j,i)) \times \pi_{out,p,j} \tag{C.6}$$

$$\rho_{ev,av} = \frac{\sum_{it=1}^{it=n_{it}} \rho_{ev,it}}{n_{it}} \tag{C.7}$$

where n_{it} is the number of iterations performed during the MC simulation.

The MC loop stops when the average cash-flow over the simulations $\rho_{ev,av}$ does not changed relatively of more than 10^{-7} between two iterations (it and $it - 1$).

In parallel, the equivalent cash-flow without any EV is computed by:

$$\rho_{noev} = \sum_{j=1}^{j=11} (G_{tot,j} \times \pi_{out,s,j} - L_{tot,j} \times \pi_{out,p,j}) \tag{C.8}$$

After that, the earning for each company c ($e_{ev,av,c}$) is computed according to the weight of its RES installation ($RES_{\%,c}$):

$$e_{ev,av,c} = RES_{\%,c} \times (\rho_{ev,av} - \rho_{noev}) \tag{C.9}$$

This value is taken into account in the computation of the mean daily cash-flow of each company c ($\rho_{d,c}$) and the remaining of the tool stays unchanged.

Example of small application

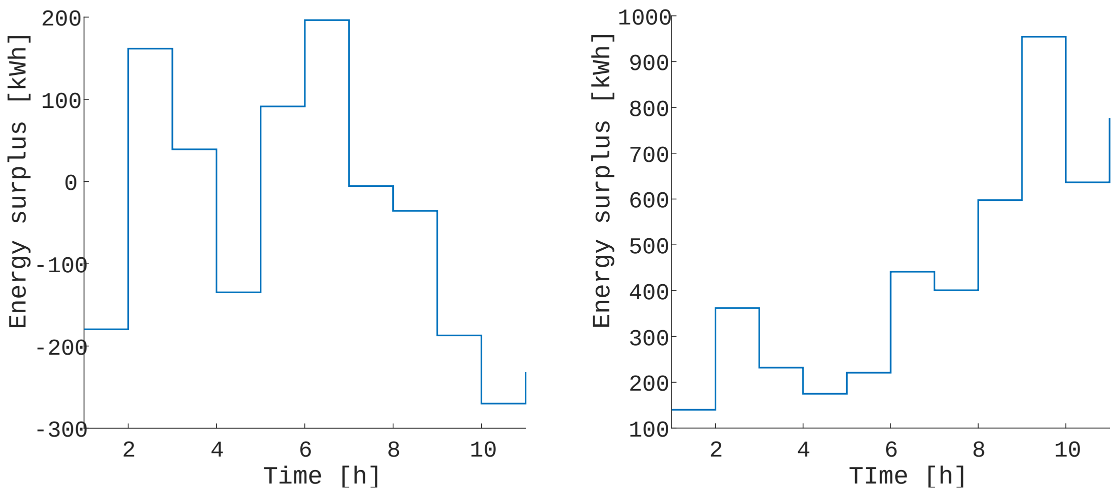
The consideration of EVs as previously presented in section is very time consuming. Indeed, for each day, the convergence of the $\rho_{ev,av}$ is reached after several minutes of simulation. Given that tens or even hundreds thousands of days may have to be simulated according to the LT plan and scenario considered, this principle can not currently be retained for a complete simulation.

However, in order to observe its application, two typical days have been simulated: one with low RESs investments and one with high RESs investments penetration. Both simulations are performed with a fleet of EVs with batteries of $40kWh$ (with $SOC_{EV,min} = 12\%$ and

$SOC_{EV,max}$ = 95%), corresponding to an amount of energy required of maximum $1660kWh$ per day. Of course, as the SOC at the arriving and departure time are randomly sampled, this amount is variable.

For the first typical day, the surplus of generation is relatively low (of about $488.6kWh$ as illustrated in Fig. C.3a), leading to the possibility of purchasing electricity inside the IMG and on the DN to complete the charge of the batteries. For such a day, the expenses of the IMG are about 76.19€ without EVs. The $\rho_{ev,av}$ with the EVs fleet is about 64.99€, with a standard deviation of 0.164 and a variance of 0.027. The precision of the simulation is therefore debatable, but the simulation time is already about 223 seconds. Note that to reach a standard deviation of less than 0.05, the simulation time is increased to about 560 seconds and the mean value remains unchanged. This difference of simulation time is quite important, given that this simulation should be carried for all the simulated days in the tool developed in this thesis.

The benefit linked to the EVs fleet, $i.e$ $76.19 - 64.99 = 11.2$€, is shared between the companies by (C.9). Note that if this average benefit is simply extrapolated to 1 year (with 5 working days a week), the global benefit is less than 3000€, which is quite a low value compared to the amount of the cash-flows inside the IMG. Of course, this value is just for information and the EVs fleet optimisation should be modified to be less time consuming and then integrated for all the simulated days in order to catch their variability and to obtain a more accurate yearly benefit value. Moreover, as the amount of surplus is limited and globally used for this day, from 30 EVs the gain is capped around this value of 11.2€.



(a) Average day. (b) Day with high RESs penetration.

Figure C.3 – Surplus of energy: example of 2 days.

The considered day with a high penetration of RESs (see Fig. C.3b) has a surplus of energy of about $4900kWh$, which may globally cover all the needs of 50 EVs batteries given that they are able to charge maximum $40kWh \times (0.95 - 0.12) = 33.2kWh$ over 1 day. For this day, ρ_{noev} is equal to 157.4€. Therefore, simulations have been conducted for higher numbers of EVs:

- With 50 EVs, $\rho_{ev,av}$ is equal to 183.7€ (with a variance of 0.019), leading to an average benefit of 26.3€;

- With 100 EVs, $\rho_{ev,av}$ is equal to 209.8€ (with a variance of 0.30), leading to an average benefit of 52.41€;
- With 150 EVs, $\rho_{ev,av}$ is equal to 236.73€ (with a variance of 0.105), leading to an average benefit of 79.36€. Note that the simulation time is around 15 minutes for this number of EVs.
- With 160 EVs, $\rho_{ev,av}$ is equal to 241.61€ (with a variance of 0.105), leading to an average benefit of 84.24€. Note that the simulation time is also around 15 minutes for this number of EVs.

As previously computed, if the latter value is extended to 1 year, it represents a benefit of around 21900€ to share between the companies, which seems already more interesting for them. Therefore, we can conclude that EVs inside the IMG can be interesting if there is an important energy surplus and a significant number of EVs.

Beyond that number of EVs, the optimisation procedure as currently implemented often do not converge with the considered profiles. The implemented procedure have thus several weaknesses: it is quickly limited in size, it has convergence issues and its computation time becomes rapidly prohibitive. Those problems should be solved in order to daily embed the presence of an EVs fleet for an in-depth analysis.

Appendix D

Additional LM results

The following tables gather all the results of the LM application for the 3 LT pricing plans with limited investments and with both fixed and variable daily pricing. The observations are globally similar to those realised for the LT plan 1 in chapter 5.

LT plan 1

s	ρ_s^{1y} [k€]	$\rho_{LM,s}^{1y}$ [k€]	$\%_s^{1y}$	SCR_s
MGEM	+243.4	+238.6	-1.99	NA
c=1	-17.11	-12.26	-23.31	68.74
c=2	-29.05	-23.57	-18.86	96.47
c=3	-7.13	-5.70	-20.04	65.59
c=4	+47.42	+89.54	+88.81	77.91
c=5	-33.06	-28.75	-13.02	82.44
c=6	+21.64	+29.15	+34.72	69.30
c=7	-42.86	-38.12	-11.04	81.30
c=8	+3.07	+10.21	+232.9	57.72
c=9	+18.17	+36.78	+102.5	74.38

Table D.1 – LT plan 1 with fixed prices - LM influence on mean daily values, on the NPVs over 1 year and new SCRs over 1 year.

s	ρ_s^{1y} [k€]	$\rho_{LM,s}^{1y}$ [k€]	$\%_s^{1y}$	SCR_s
MGEM	+243.4	+238.6	-1.96	NA
c=1	-17.11	-10.37	-39.41	68.73
c=2	-29.05	-22.74	-21.71	96.47
c=3	-7.13	-5.10	-28.48	65.57
c=4	+47.42	+95.21	+100.77	77.91
c=5	-33.06	-26.99	-18.34	82.44
c=6	+21.64	+29.60	+36.80	69.30
c=7	-42.86	-36.21	-15.51	81.30
c=8	+3.07	+13.49	+339.9	57.72
c=9	+18.17	+41.23	+126.9	74.38

Table D.2 – LT plan 1 with variable daily pricing - LM influence on mean daily values, on the NPVs over 1 year and new SCRs over 1 year.

LT plan 2

s	ρ_s^{1y} [k€]	$\rho_{LM,s}^{1y}$ [k€]	$\%_s^{1y}$	SCR_s
MGEM	+236.4	+232.3	-1.74	NA
c=1	-17.11	-12.58	-26.48	64.11
c=2	-29.72	-24.36	-18.39	96.90
c=3	-7.37	-5.95	-19.19	62.02
c=4	+42.92	+82.89	+93.11	82.93
c=5	-33.50	-29.31	-12.51	80.42
c=6	+21.55	+28.94	+34.31	70.80
c=7	-43.64	-38.85	-10.98	76.22
c=8	+3.06	+9.95	+225.26	52.56
c=9	+61.45	+77.41	+25.98	73.90

Table D.3 – LT plan 2 with fixed prices - LM influence on mean daily values, on the NPVs over 1 year and new SCRs over 1 year.

s	$\%_{1,s}$	$\%_{2,s}$	$\%_{3,s}$	$\%_{4,s}$	$\%_{5,s}$
c=1	84.11	81.21	60.96	80.97	81.82
c=3	68.54	84.60	80.79	65.03	62.84
c=6	84.43	81.99	79.54	84.68	78.99
c=7	64.88	85.00	70.68	67.24	49.86
c=8	95.29	99.08	98.99	90.34	86.62

Table D.4 – LT plan 2 - LM occurence over 1 year (with fixed prices).

s	ρ_s^{1y} [k€]	$\rho_{LM,s}^{1y}$ [k€]	$\%_s^{1y}$	SCR_s
MGEM	+236.4	+232.5	-1.67	NA
c=1	-17.11	-11.33	-33.80	64.07
c=2	-29.72	-23.70	-20.26	96.90
c=3	-7.37	-5.53	-24.87	62.00
c=4	+42.92	+87.54	+103.9	82.93
c=5	-33.50	-28.10	-16.10	80.42
c=6	+21.55	+29.26	+35.77	70.79
c=7	-43.64	-37.50	-14.05	76.21
c=8	+3.06	+12.17	+297.7	52.55
c=9	+61.45	+79.95	+30.12	73.89

Table D.5 – LT plan 2 with variable daily pricing - LM influence on mean daily values, on the NPVs over 1 year and new SCRs over 1 year.

s	$\%_{1,s}$	$\%_{2,s}$	$\%_{3,s}$	$\%_{4,s}$	$\%_{5,s}$
c=1	83.98	80.84	60.86	80.35	81.15
c=3	68.28	84.33	80.79	64.99	62.50
c=6	83.91	81.83	79.51	84.05	78.45
c=7	64.42	84.93	70.54	66.86	49.39
c=8	95.03	98.80	98.75	89.51	86.08

Table D.6 – LT plan 2 - LM occurence over 1 year (with variable daily pricing).

LT plan 3

s	ρ_s^{1y} [k€]	$\rho_{LM,s}^{1y}$ [k€]	$\%_s^{1y}$	SCR_s
MGEM	+210.1	+206.0	-1.92	NA
c=1	-16.44	-11.65	-29.15	70.66
c=2	-28.17	-22.86	-18.83	96.75
c=3	-6.89	-5.43	-21.22	67.26
c=4	+47.30	+84.60	+78.85	80.22
c=5	-31.98	-27.65	-13.54	83.46
c=6	+21.59	+28.66	+32.73	70.49
c=7	-41.53	-36.88	-11.21	81.93
c=8	+3.09	+10.12	+228.1	60.20
c=9	+119.0	+130.5	+9.68	63.33

Table D.7 – LT plan 3 with fixed prices - LM influence on mean daily values, on the NPVs over 1 year and new SCRs over 1 year.

s	$\%_{1,s}$	$\%_{2,s}$	$\%_{3,s}$	$\%_{4,s}$	$\%_{5,s}$
c=1	83.02	78.80	57.72	80.75	80.09
c=3	66.77	81.10	78.37	65.63	59.34
c=6	82.95	79.53	72.65	82.10	76.80
c=7	64.43	83.17	67.91	67.39	49.23
c=8	94.58	99.23	99.37	88.59	84.76

Table D.8 – LT plan 3 - LM occurence over 1 year (with fixed prices).

s	ρ_s^{1y} [k€]	$\rho_{LM,s}^{1y}$ [k€]	$\%_s^{1y}$	SCR_s
MGEM	+210.1	+206.0	-1.93	NA
c=1	-16.44	-9.19	-44.07	70.66
c=2	-28.17	-21.78	-22.67	96.75
c=3	-6.89	-4.64	-32.61	67.26
c=4	+47.30	+95.56	+102.01	80.22
c=5	-31.98	-25.39	-20.59	83.46
c=6	+21.59	+29.27	+35.54	70.49
c=7	-41.53	-34.40	-17.17	81.93
c=8	+3.09	+14.3	+363.5	60.20
c=9	+119.0	+134.6	+13.15	63.33

Table D.9 – LT plan 3 with variable daily pricing - LM influence on mean daily values, on the NPVs over 1 year and new SCRs over 1 year (VAR)

s	$\%_{1,s}$	$\%_{2,s}$	$\%_{3,s}$	$\%_{4,s}$	$\%_{5,s}$
c=1	83.02	78.80	57.72	80.58	80.02
c=3	66.83	81.13	78.37	65.51	59.26
c=6	82.95	79.53	72.61	81.88	76.80
c=7	64.43	83.17	67.87	67.20	49.16
c=8	94.71	99.23	99.33	88.42	84.61

Table D.10 – LT plan 3 - LM occurence over 1 year (with variable daily pricing).

LT plan 1 with $r_P = 0.3$

s	ρ_s^{1y} [k€]	$\rho_{LM,s}^{1y}$ [k€]	$\%_s^{1y}$	SCR_s
MGEM	+244.8	+239.5	-2.16	NA
c=1	-18.22	-10.20	-44.02	66.15
c=2	-29.64	-22.26	-24.88	96.90
c=3	-7.48	-5.02	-32.93	63.69
c=4	+67.27	+119.9	+78.33	76.54
c=5	-33.95	-26.65	-21.51	81.51
c=6	+21.02	+29.90	+42.25	70.91
c=7	-43.45	-35.54	-18.19	77.37
c=8	+1.29	+13.50	+943.6	55.61
c=9	+79.44	+100.5	+26.50	72.26

Table D.11 – LT plan 1 with $r_P = 0.3$ and variable daily pricing - LM influence on mean daily values, on the NPVs over 1 year and new SCRs over 1 year.

Appendix E

Unlimited investments wiht the IEO as MGEM

The following results are relative to the simulation of the 3 LT pricing plans with unlimited investments and with the IEO as MGEM. The trends of the results are quite similar to those presented with limited investments except that the cash-flows of the IEO are higher (see Tab. E.1, E.2 a,d E.3) and the losses of the MGEM are increased (see Tab. E.5, E.11 and E.17).

The other parameters of analysis are similar to the results obtained with unlimited investments and the DSO as MGEM.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
IEO/MGEM	460.74	482.36	381.12	465.32	557.82	445.06	438.86	452.27	373.98

Table E.1 – LT plan 1 - Unlimited IEO cash-flows [k€].

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
IEO/MGEM	379.25	485.93	379.85	457.64	555.42	448.34	395.24	457.43	375.17

Table E.2 – LT plan 2 - Unlimited IEO cash-flows [k€].

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
IEO/MGEM	227.56	258.06	178.14	252.28	275.27	213.75	213.76	230.53	178.14

Table E.3 – LT plan 3 - Unlimited IEO cash-flows [k€].

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
Eq.	9	27	9	18	27	9	9	27	9
$\sum I_{simu,d}$	5740	10422	5699						

Table E.4 – LT plan 1 unlimited IEO - Equilibrium and number of simulated days analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
DSO	-31.9	-36.0	-32.3	-26.8	-36.5	-31.8	-29.7	-31.8	-31.2
c=1	-24.5	-25.3	-24.6	-23.3	-30.3	-23.8	-26.1	-31.5	-26.2
c=2	-56.5	-59.2	-53.4	-55.4	-56.7	-53.7	-66.9	-70.6	-63.2
c=3	-25.1	-33.1	-25.2	-29.4	-37.0	-23.9	-26.0	-40.8	-26.1
c=4	-173	-157	-192	-185	-165	-189	-177	-170	-185
c=5	-21.6	-24.7	-21.5	-22.3	-28.3	-20.8	-22.4	-29.6	
c=6	-549	-452	-688	-413	-343	-507	-822	-678	-1061
c=7	-21.6	-24.6	-21.7	-22.2	-27.6	-20.8	-22.6	-29.2	-22.5
c=8	-64.4	-72.4	-55.4	-67.0	-71.4	-61.0	-80.9	-90.0	-70.7
c=9	-189	-177	-210	-257	-192.3	-220	-238	-233	-242

Table E.5 – LT plan 1 unlimited IEO - Gains/losses analysis for each scenario [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
1	8.29	8.93	8.21	8.74	8.76	8.11	8.26	8.37	7.92
2	88.85	85.24	88.98	86.77	85.59	88.44	88.71	84.55	89.06
3	2.58	4.66	2.70	4.07	4.72	3.24	2.44	5.14	2.40
4	0.28	1.16	0.11	0.41	0.92	0.20	0.60	1.95	0.62

Table E.6 – LT plan 1 unlimited IEO - Daily pricing percentages [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
TIC [kW]	12429	14632	12429	13531	14632	12429	12429	14632	12429
REP [%]	1.38	1.50	1.37	1.33	1.45	1.26	1.49	1.69	1.47
IEP [%]	89.99	82.73	90.06	85.14	82.64	88.19	91.95	82.75	91.77

Table E.7 – LT plan 1 unlimited IEO - Internal exchanges analysis.

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
PP [%]	48.53	43.81	48.92	49.03	45.28	51.88	45.41	39.46	46.01
SP [%]	51.47	56.19	51.08	50.97	54.72	48.12	54.89	60.54	53.99

Table E.8 – LT plan 1 unlimited IEO - External exchanges analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
c=1	NA	40.65	NA	54.85	43.52	NA	NA	35.91	NA
c=2	66.41	64.50	67.34	77.08	75.19	75.20	58.21	57.81	58.20
c=3	NA	35.67	NA	54.09	39.28	NA	NA	31.42	NA
c=4	46.25	46.89	46.89	50.06	44.41	49.19	46.63	43.57	46.51
c=5	NA	47.87	NA	75.45	53.90	NA	NA	42.37	NA
c=6	25.32	23.40	25.91	32.15	30.45	30.46	21.15	20.23	21.09
c=7	NA	52.06	NA	71.35	56.23	NA	NA	46.51	NA
c=8	30.66	34.29	30.33	31.76	37.01	36.63	27.04	30.90	27.94
c=9	41.44	39.69	41.72	40.18	39.79	39.17	39.16	36.80	39.28

Table E.9 – LT plan 1 unlimited IEO - Self-consumption rates [%].

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
Eq.	18	27	9	27	27	9	9	27	9
$\sum I_{simu,d}$	7694	11039	5688		62551	31133	43011	43343	27523

Table E.10 – LT plan 2 unlimited IEO - Equilibrium and number of simulated days analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
MGEM	-32.8	-32.7	-30.0	-30.1	-38.4	-26.2	-35.3	-35.7	-30.1
c=1	-21.3	-27.4	-22.8	-23.1	-31.3	-21.4	-22.2	-33.6	-23.5
c=2	-59.8	-60.3	-55.3	-55.7	-57.3	-53.5	-68.1	-72.3	-64.4
c=3	-28.0	-34.9	-23.0	-31.4	-38.1	-21.7	-33.0	-43.4	-23.5
c=4	-200	-159	-212	-190	-161	-194	-174	-177	-193
c=5	-20.4	-25.4	-19.5	-22.0	-28.0	-18.1	-21.5	-30.5	-19.6
c=6	-600	-481	-728	-428	-359	-513	-864	-712	-1117
c=7	-20.4	-24.8	-19.5	-21.7	-26.9	-18.3	-21.5	-29.4	-19.6
c=8	-73.5	-78.2	-62.2	-70.7	-75.8	-63.7	-86.5	-97.3	-75.8
c=9	-237	-190	-267	-214	-190	-267	-210	-193	-229

Table E.11 – LT plan 2 unlimited IEO - Gains/losses analysis for each scenario [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
1	20.96	22.78	22.40	22.56	21.81	23.51	21.82	21.60	24.55
2	62.31	59.08	69.23	59.06	59.96	66.83	57.25	57.82	66.98
3	16.09	17.10	8.30	17.70	17.51	9.54	19.38	19.00	8.07
4	0.64	1.03	0.07	0.68	0.72	0.12	1.55	1.57	0.40

Table E.12 – LT plan 2 unlimited IEO - Daily pricing percentages [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
TIC [kW]	13531	14632	12429	14632	14632	12429	14632	14632	12429
REP [%]	1.65	1.52	1.57	1.45	1.46	1.33	1.69	1.71	1.49
IEP [%]	85.62	82.80	90.96	82.34	82.54	88.84	82.92	82.88	91.86

Table E.13 – LT plan 2 unlimited IEO - Internal exchanges analysis.

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
PP [%]	40.89	43.43	43.64	45.29	45.01	49.68	39.27	39.10	45.51
SP [%]	59.11	56.57	56.36	54.71	54.99	50.32	60.73	60.90	54.49

Table E.14 – LT plan 2 unlimited IEO - External exchanges analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
c=1	55.54	41.38	NA	44.08	45.25	NA	35.9	35.26	NA
c=2	65.85	65.63	65.71	73.96	75.64	74.75	57.46	58.31	58.50
c=3	52.03	36.15	NA	39.64	40.50	NA	31.19	30.69	NA
c=4	40.56	46.89	41.42	45.26	43.72	46.08	43.25	42.62	46.22
c=5	70.24	48.41	NA	54.03	54.90	NA	42.13	41.68	NA
c=6	24.64	24.17	24.18	29.34	30.82	30.10	20.20	20.82	21.18
c=7	70.26	53.15	NA	56.77	57.62	NA	46.17	45.55	NA
c=8	31.87	34.94	32.29	37.63	38.26	36.88	30.97	30.03	27.55
c=9	36.26	38.55	35.78	38.53	38.90	36.66	37.37	37.80	39.22

Table E.15 – LT plan 2 unlimited IEO - Self-consumption rates [%].

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
Eq.	9	18	9	9	27	9	9	18	9
$\sum I_{simu,d}$	6098	7475	5358	31393		32182	26459	49891	27500

Table E.16 – LT plan 3 unlimited IEO - Equilibrium and number of simulated days analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
MGEM	-32.8	-34.8	-33.7	-34.5	-31.6	-34.7	-28.9	-36.0	-35.3
c=1	-28.1	-26.1	-29.4	-26.8	-29.0	-26.8	-29.0	-29.3	-28.9
c=2	-55.5	-58.3	-52.7	-56.1	-56.5	-54.2	-66.2	-67.4	-62.2
c=3	-28.2	-31.9	-29.8	-27.4	-35.9	-27.5	+29.0	-36.0	-28.9
c=4	-162	-136	-203	-180	-164	-185	-182	-163	-178
c=5	-25.0	-25.4	-26.7	-24.2	-28.3	-24.2	-25.5	-28.1	-25.5
c=6	-512	-430	-645	-395	-326	-482	-779	-611	-990
c=7	-24.9	-25.2	-26.8	-24.4	-28.2	-24.4	-25.6	-27.9	-25.5
c=8	-60.3	-67.5	-49.9	-64.3	-66.7	-58.5	-75.9	-80.3	-64.7
c=9	-186	-170	-241	-201	-209	-226	-211	-180	-219

Table E.17 – LT plan 3 unlimited IEO - Gains/losses analysis for each scenario [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
1	0.06	0.05	0.02	0.05	0.05	0.06	0.05	0.04	0.04
2	99.26	98.84	99.61	99.68	98.83	99.70	99.29	98.36	99.16
3	0.11	0.08	0.07	0.11	0.11	0.09	0.6	0.10	0.11
4	0.57	1.03	0.30	0.16	1.01	0.15	0.60	1.50	0.69

Table E.18 – LT plan 3 unlimited IEO - Daily pricing percentages [%].

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
TIC [kW]	12429	13531	12429	12429	14632	12429	12429	13531	12429
REP [%]	1.37	1.33	1.57	1.34	1.47	1.32	1.49	1.62	1.45
IEP [%]	90.40	85.85	90.65	88.89	82.43	88.74	91.84	85.85	91.76

Table E.19 – LT plan 3 unlimited IEO - Internal exchanges analysis.

	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
PP [%]	48.06	49.07	43.57	49.53	44.51	50.17	45.47	41.62	46.59
SP [%]	51.94	50.93	56.43	50.47	55.49	49.83	54.53	58.38	53.41

Table E.20 – LT plan 3 unlimited IEO - External exchanges analysis.

s	Ψ_1	Ψ_2	Ψ_3	Ψ_4	Ψ_5	Ψ_6	Ψ_7	Ψ_8	Ψ_9
c=1	NA	56.20	NA	NA	44.71	NA	NA	48.68	NA
c=2	66.72	66.70	67.54	74.81	74.50	75.02	58.15	57.29	58.52
c=3	NA	52.45	NA	NA	40.16	NA	NA	44.88	NA
c=4	45.23	52.60	39.66	45.41	43.83	45.43	47.30	44.87	48.30
c=5	NA	70.51	NA	NA	54.58	NA	NA	61.27	NA
c=6	25.76	25.20	26.43			29.88	20.76	20.60	21.30
c=7	NA	71.96	NA	NA	57.30	NA	NA	62.78	NA
c=8	32.77	31.51	31.77	35.96	38.63	35.34	27.89	26.97	27.60
c=9	41.46	40.47	36.24	37.99	39.01	39.84	37.81	38.24	38.14

Table E.21 – LT plan 3 unlimited IEO - Self-consumption rates [%].

Appendix F

Summary of all percentages of the companies

The following figures gather all the saving percentages of each company for the 6 LT plans simulated according to the 9 scenarios, as previously presented in the results in chapter 5.

As previously observed, the benefits of companies 2, 4, 6, 8 and 9 are globally increased with unlimited investments while those of the other companies remain quite stable.

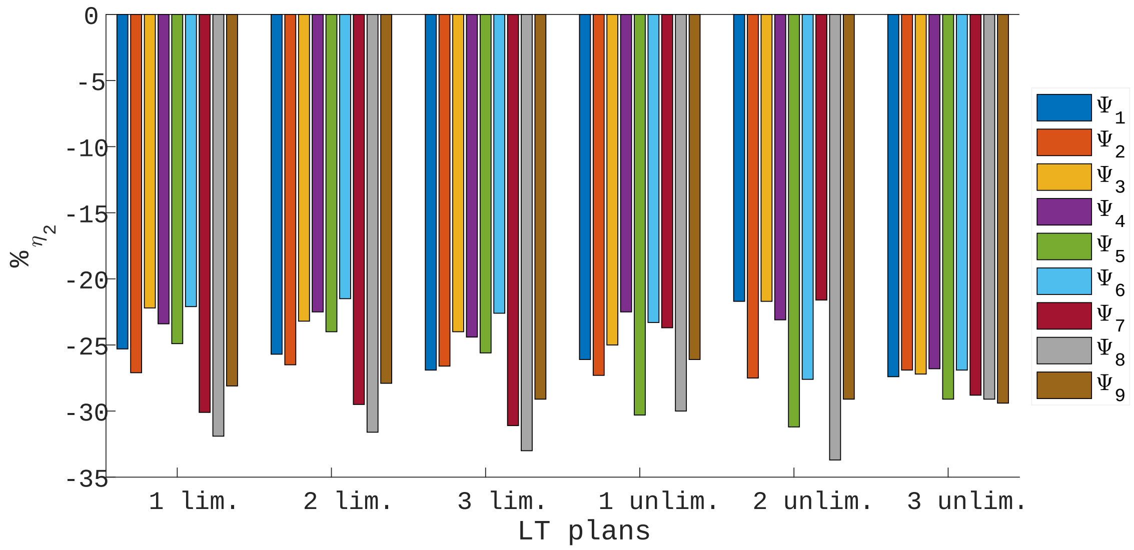


Figure F.1 – Percentages of gains of the company 1.

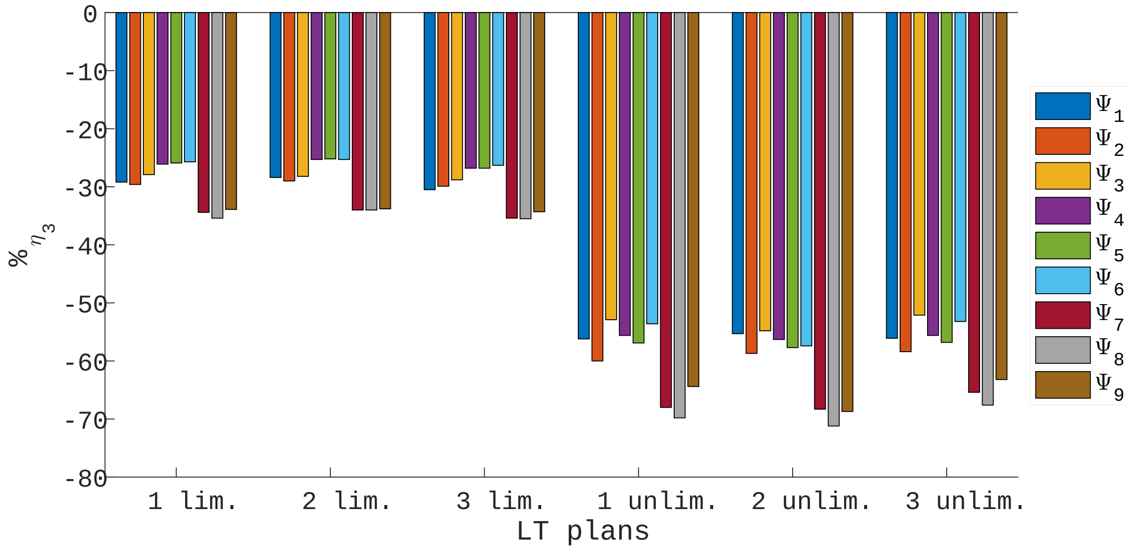


Figure F.2 – Percentages of gains of the company 2.

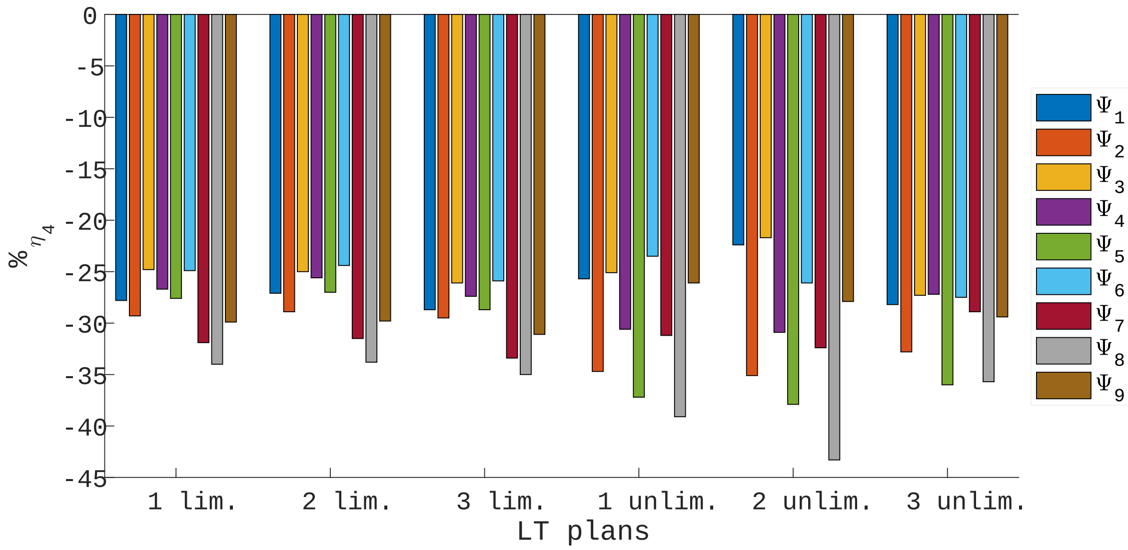


Figure F.3 – Percentages of gains of the company 3.

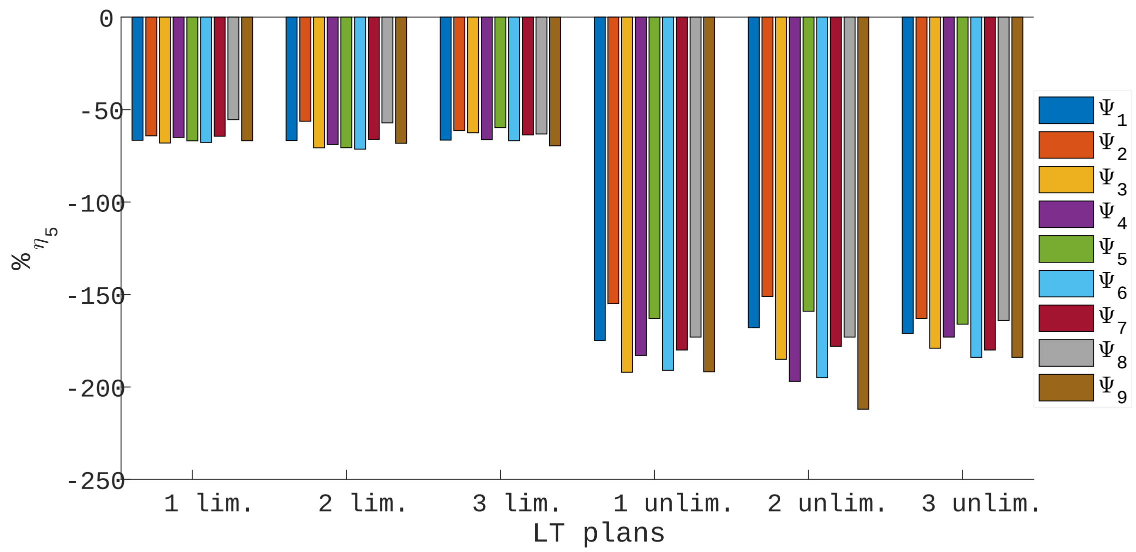


Figure F.4 – Percentages of gains of the company 4.

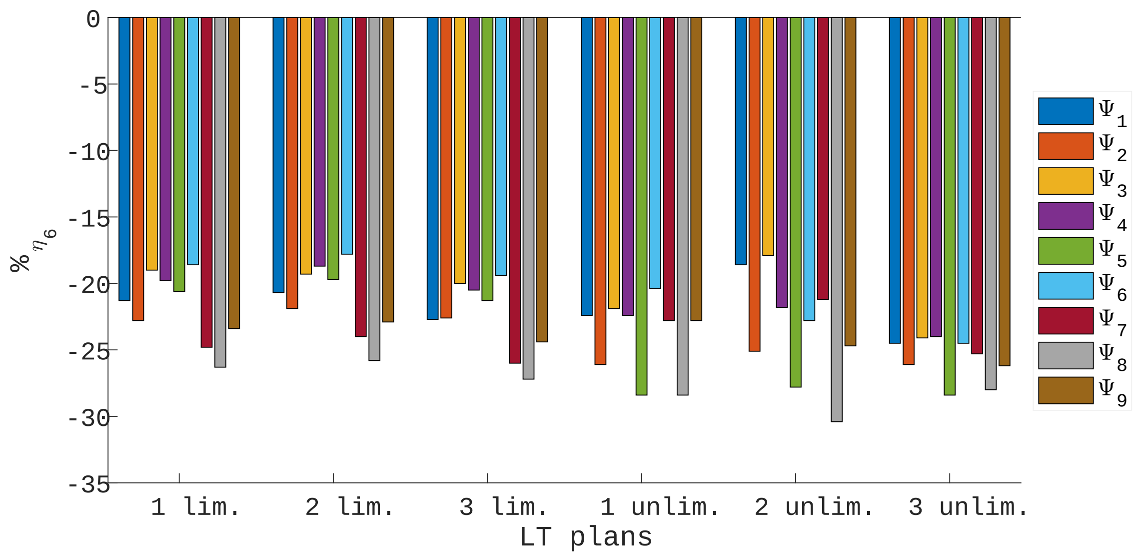


Figure F.5 – Percentages of gains of the company 5.

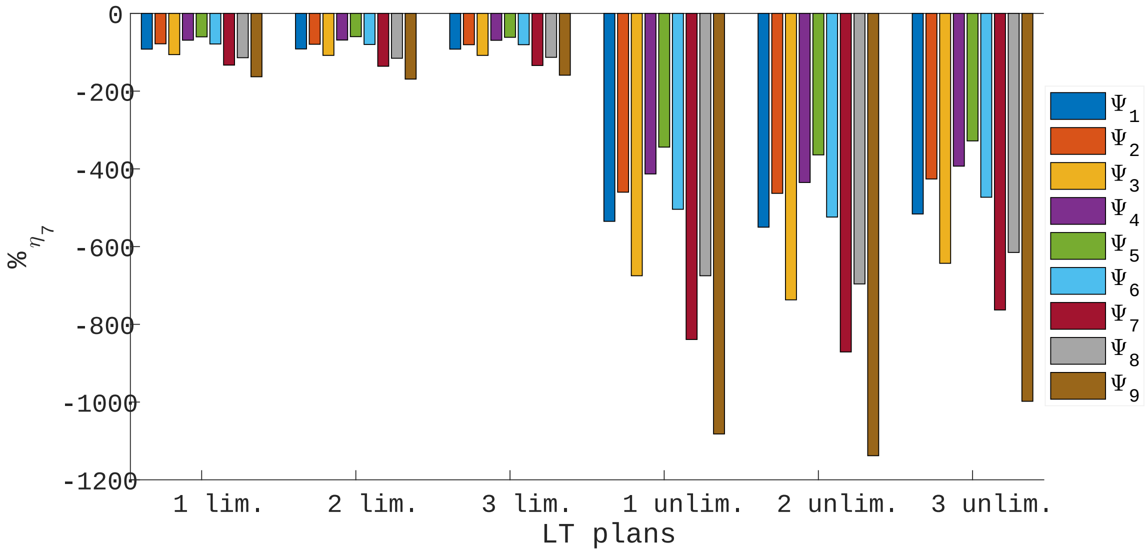


Figure F.6 – Percentages of gains of the company 6.

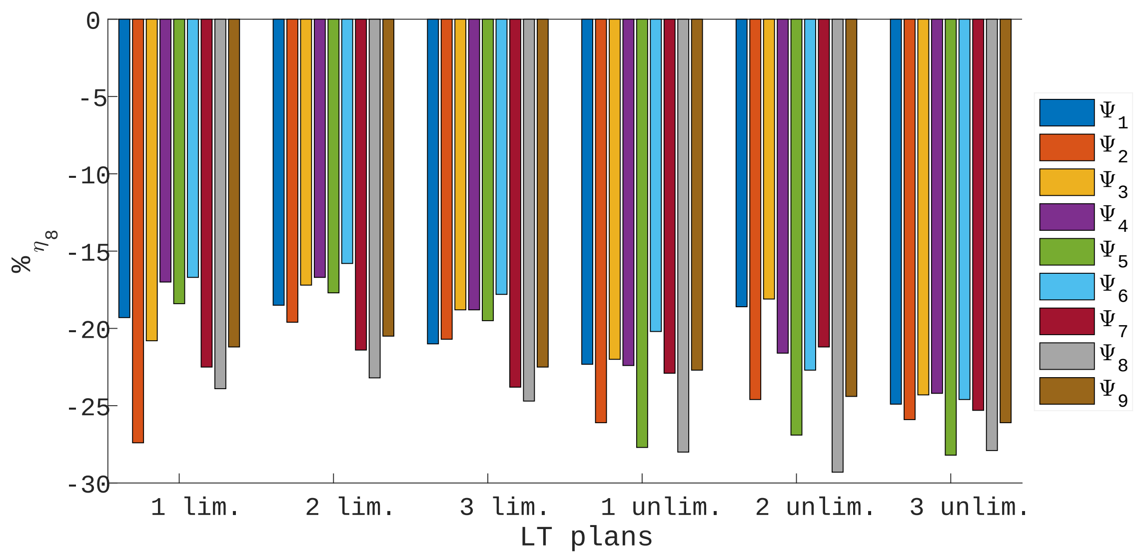


Figure F.7 – Percentages of gains of the company 7.

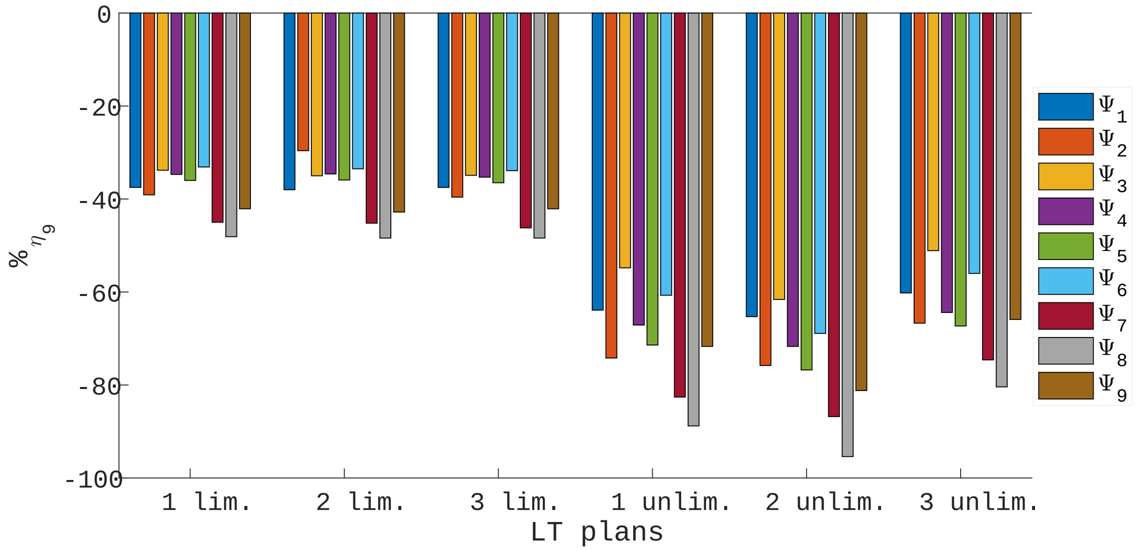


Figure F.8 – Percentages of gains of the company 8.

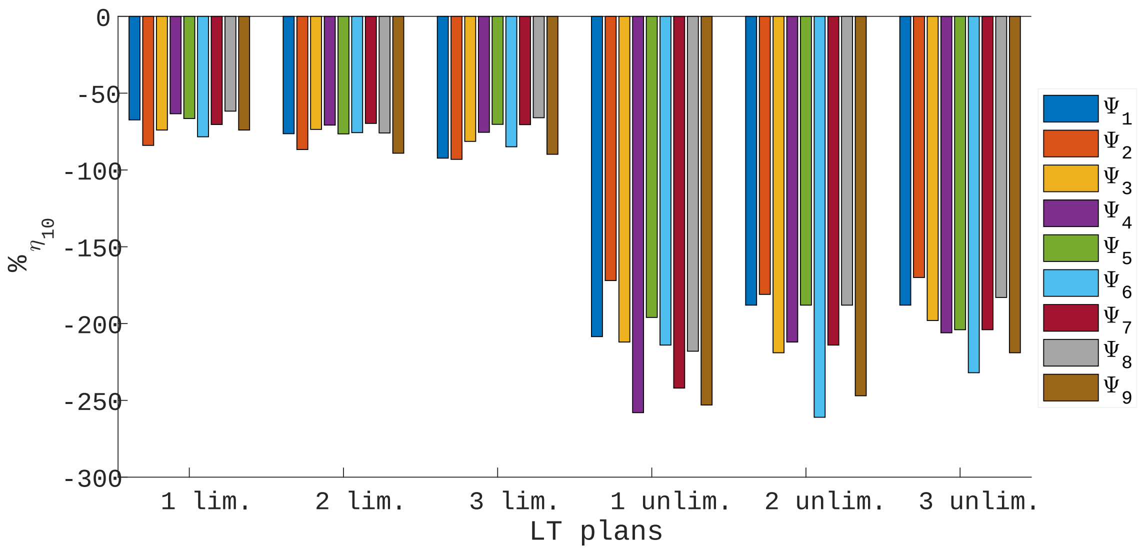


Figure F.9 – Percentages of gains of the company 9.