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Optimized management of dispatchable thermal loads in retail industry for the supply of ancillary services

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Abstract

In recent years, Italy has experienced deep changes due to the high penetration of renewable plants for the production of electricity. In the coming years these changes will be more evident given the objectives that our country wants to achieve by 2030. It is clear that a radical change in electricity generation plants is directly linked to the need for a reform of the electricity market and, in particular, of the ancillary services one. For this reason, ARERA opened the market to new participants in 2017 through Decree 300/2017/R/eel. Since then, three pilot projects have been carried out with the aim of finding new resources for the ancillary services market.

The purpose of this thesis is to assess the profitability of the participation in the MSD for the owner of a consumption unit (a supermarket) belonging to a UVAM (Mixed Virtual Enabled Unit).

The first part of the work is focused on the changes that Italy is facing and that will face in the near future, explaining the critical issues of a high penetration of Renewable Energy Sources (RES).

The second part analyses the UVAM pilot project. First, from a regulatory point of view, in order to indicate what are the rules that the UVAM must comply with in order to participate in the MSD. The results of the pilot project, referring to the year 2019, are then presented to understand whether the UVAMs are already being used as innovative solutions for the supply of ancillary services. The results show that, during the last year, Terna did not send them a large number of dispatching orders, which means that the UVAMs have yet to demonstrate their full potential.

In the third part, the MILP optimization model used for the numerical analysis is presented. In particular, the supermarket's participation in the MSD has been added to the model developed in [21]. The supermarket can provide increasing balancing services by shifting its electrical consumption thanks to the thermal capacity of its refrigeration units. In this work, it is assumed that the UVAM is composed of consumption units of the same type. The results of the optimization process are two different operative scenarios of the supermarket: the "base" and the "call". The former represents an operative condition in which the supermarket is able to provide the service, but the dispatching order is not sent by the TSO. The latter is the operation of the unit when it must actually execute the

dispatching order. As the operative scenarios are computed simultaneously, the objective function of the model is the sum of the operating costs of the scenarios, weighed on the probability that the scenarios will occur.

The fourth chapter analyses the profitability of the supermarket's participation in the MSD. The analysis is divided into four parts. First, the lower bound of the operating costs of the supermarket is obtained by optimizing the management of the dispatchable thermal loads with the aim of minimizing the operating costs, without taking into account the participation in the ancillary services market. Then, by giving a null probability to the "call" operating scenario in the objective function of the model, the minimum cost increase that allows to perform an offer in the MSD is found. In this case, the economic impact caused by the execution of a dispatching order sent by TSO is not considered relevant. Next, giving a probability to the "call" operating scenario equal to 5% in the objective function, the minimum number of units that guarantee the highest annual income is found. The annual analysis is carried out taking into account different frequencies of the days in which a dispatching order is received from Terna. Finally, a sensitivity analysis is carried out to study the impact that the statistical weight of the "call" operating scenario has on the solution of the optimization process.

The results show that the participation of the supermarket in the MSD is not very profitable, although many dispatching orders are sent by Terna and that the most profitable UVAM's architecture results to be the one constituted by at least four units, offering 250 kW each.

Keywords

UVAM – Consumption units – Ancillary services – Flexibility - Optimization

1 The need of new resources for ancillary services supply

In the last few years, Italy is facing important changes regarding its electricity power production plants. These changes will be more visible in the future years since the country is pushing towards a huge penetration of renewable energy sources to face environmental issues that are affecting Italy and the entire world in general. A massive penetration of renewable energy sources for electricity production is obviously related to a direct impact on the electricity market and should be supported by a suitable legislation. The purpose of this chapter is to give an overview on the goals that Italy wants to achieve in the next ten years, and which trend the electricity market is currently following. This is important to understand why ARERA, the Italian authority for the regulation of the electrical grid, is pushing towards a deep reform of the Ancillary Service market, and why Terna, the Italian TSO[1], opened the market to new participants through the so called pilot projects.

1.1 The PNIEC: goals to 2030

The PNIEC[2] [1], has been published in December 2019 by the Italian Ministry of Economic Development (MISE), and includes the strategies that the country must follow to achieve both energetic and environmental goals planned until 2030. In particular, the PNIEC is focused on energetic strategies in terms of:

- Accelerating the decarbonization process, being aware that the 2030 will be an intermediate step towards a deeper decarbonization until 2050.
- Encouraging, in particular in the electric sector, a switch from the historical centralised approach to a modern distributed one.
- Promoting the energetic efficiency to ensure lower expenses to both industrial and civil users.
- Promoting a wider electrification of consumptions with particular focus on the civil and transportation sectors, also to improve the air quality in the cities.

In the PNIEC, a central role is given to the Renewable Energy Sources (RES). In fact, a huge share of the gross final energy consumption is foreseen to be covered by electricity

[1] The TSO is the Transmission System Operator. Its role is to ensure the safety of the transmission grid.
[2] PNIEC stands for: Piano Nazionale Integrato per l’Energia e il Clima.

produced by renewable power plants. The goals, in terms of renewable energy penetration, are shown in the following (Table 1 and figure 1). The data are taken from the PNIEC itself and from the *Renewable Energy Report 2019* [2].

In Italy, the prevision is that electricity produced by RES will be able to cover the 30% of the gross final energy consumption in 2030 determining a huge increase with respect to the 17% of 2020. Table 1 shows the objectives of Italy compared to the ones of the UE until 2030, while Figure 1 represents the expected growth of energy consumption covered by RES.

	UE 2020	Italy 2020	UE 2030	Italy 2030
% of energetic consumption covered by RES	20%	17%	32%	30%

Table 1: percentage of the gross final energetic consumption covered by RES

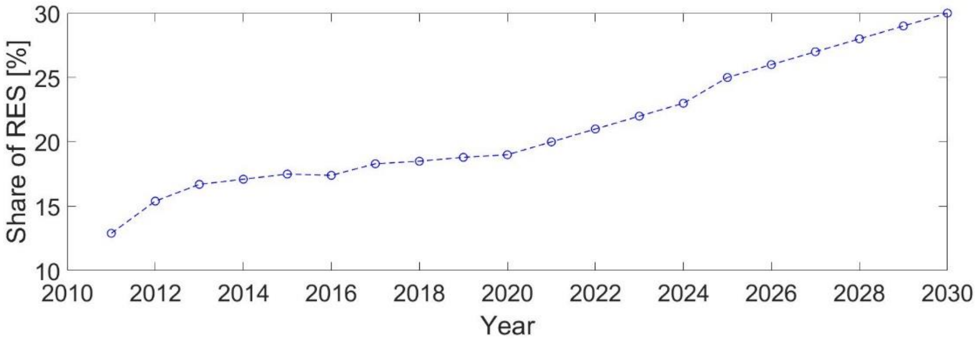

Figure 1: Share of RES in the final gross electricity consumption

More specifically, in the PNIEC, the prevision of the penetration of energy produced by RES is further divided in three main sectors that are the electricity generation, the thermal sector and the transportation sector as shown in Table 2.

Sector	% covered by RES
Electricity Generation	55.4%
Thermal	33%
Transportation	21.6%

Table 2: percentage of energy consumption covered by RES divided in three sectors

Of course, a growth of the RES penetration has to be coupled with a higher installed renewable power. Specifically, the growth of installed Eolic and Solar power is predicted to be particularly high. In fact, in 2030 the installed Eolic (on and off-shore) power will almost be the double of the 2017 one while, the installed Solar (PV and CSP) power will be more than the double of the one installed in 2017 (Table 3). Nevertheless, it is important to highlight that these objectives do not have to be reached just by promoting the construction of new plants, but it is fundamental to push towards a revamping and repowering process of the existing plants.

Source	Installed Power [MW]			Growth 2017-2030
	2017	2025	2030	
Hydro	18863	19140	19200	+2%
Geothermal	813	919	950	+17%
Eolic	9766	15690	18400	+88%
Bioenergy	4135	3570	3764	-9%
Solar	19862	26840	50880	+158%

Table 3: goals in terms of installed renewable power

Additionally, the electrification of consumptions is a key aspect needed to reach a deep and effective penetration of renewable energy sources inside the national electric system. The main sectors that can benefit from a larger use of electricity coming from RES are the thermal and the transportation ones. In fact, as stated in the PNIEC, in the next years it will be crucial to promote efficient devices for ambient heating and cooling and to encourage the adoption of more environmentally friendly vehicles:

- According to the goals that Italy wants to achieve in 2030, a deep technological change will be required in the thermal sector. Particular emphasis will be put on heat pumps whose electricity consumption is estimated to double in 2030. At the same time, a policy focusing on the dismission of obsolete combustion devices in favour of more efficient solutions is needed.
- A non-negligible contribution is also expected from the transportation sector through the adoption of full-electric and hybrid vehicles both for private and public mobility. In ten years, it is expected the presence of almost six million of sustainable vehicles both BEV (Battery Electric Vehicles) and PHEV (Plug-in Hybrid Electric Vehicles). It is indeed foreseen the introduction of a mandatory share of electric vehicles for public mobility in Italian cities.

As mentioned above, a large penetration of RES in the electric system has a direct impact on the electricity market dynamics. The impact is already visible and will be better explained in the following paragraph.

1.2 The current evolution of the Italian electricity market

Nowadays, the Italian electricity market is divided into three main sub-markets that are: The Day-Ahead market (or MGP[3]), the Infra-Day market (or MI[4]) and the Ancillary Services Market (or MSD[5]):

1. The MGP is an auction market in which participants submit their bids (or asks) specifying the minimum (or maximum) price at which they want to sell (or purchase) energy. The MGP sitting opens at 8 a.m. on the ninth day (day D-9) before the delivery day and closes the day before the delivery (day D-1) at 12 p.m. The acceptance of the bids/asks is known when the MGP sitting is closed, the process follows an economic merit order and takes into account the transmission capacity limits between different geographical zones. The transmission grid is in fact divided in six zones that are: northern Italy (NORD), central-northern Italy (CNOR), central-southern Italy (CSUD), southern Italy (SUD), Sicily (SICI) and Sardinia (SARD). The offers acceptance process occurring in the MGP can be summarised as follows:

- Demand offers are ordered by increasing price.
- Supply offers are ordered by decreasing price.
- The intersection between the energy demand and supply curves represent the equilibrium price, also called clearing price (figure 2). If there are no violations of the transmission capacity of the lines, the clearing price is kept equal for every geographical area. Finally, the accepted bids are the ones characterised by a price lower than the equilibrium one, while the opposite happens for the accepted asks.
- Whenever a violation of the transmission capacity occurs, the market is divided in two market zones. The export zone which is the one downstream the violation and the import zone that is the one upstream the violation. For both these zones the process for the equilibrium price definition is repeated and two zonal prices

[3] MGP stands for Mercato del Giorno Prima
[4] MI stands for Mercato Infragiornaliero
[5] MSD stands for Mercato dei Servizi di Dispacciamento

are found. If capacity constraints are violated again, the zone-splitting process continues until no limit is violated.

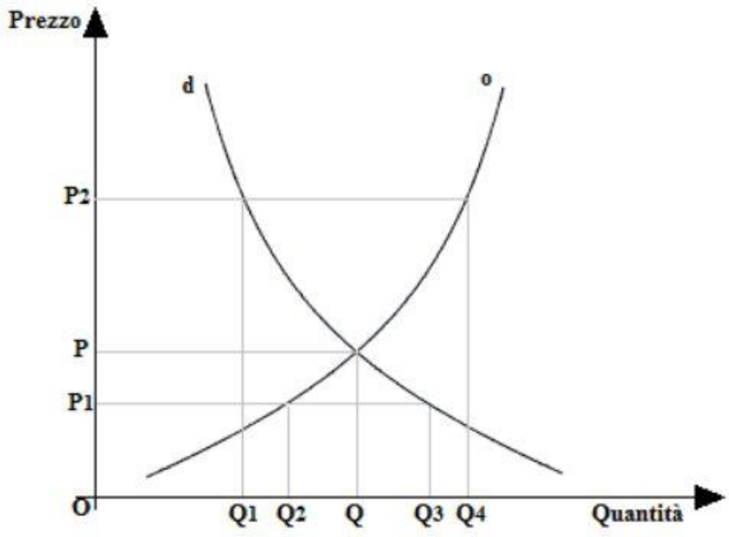

Figure 2: clearing price definition during the MGP

The GME[6] acts as a central counterpart in the MGP.

2. The MI is an adjustment market sub-phase in which the participants can modify their scheduled power profiles previously defined in the MGP. It is necessary to allow the respect of the plants' technical limits after the MGP closure and to update the submitted profiles that may change according to better previsions available closer to the delivery day. The MI is structured in seven session that take place the day before the delivery time (day D-1) as represented in figure 3. As it occurs in the MGP, also in this case the power limits at zonal level are evaluated and the offers selection criterion works analogously to the MGP one. Of course, some rules have been established to avoid the possibility for consumers to buy energy in the MGP and sell it at a higher price during the MSD. Also for the MI, the GME acts as a central counterpart.

[6] GME stands for Gestore dei Mercati Energetici and is the Italian company responsible for the management of the energy market.

Giorno di riferimento	D-1				D															
	MGP	MI1	MI2	MSD1	MB1	MI3	MSD2	MB2	MI4	MSD3	MB3	MI5	MSD4	MB4	MI6	MSD5	MB5	MI7	MSD6	MB6
Informazioni preliminari	11.30	15.00	16.30	n.d.	n.d.	23.45*	n.d.	n.d.	3.45	n.d.	n.d.	7.45	n.d.	n.d.	11.15	n.d.	n.d	15.45	n.d.	n.d
Apertura seduta	08.00**	12.55	12.55	12.55	°	17.30*	°	22.30*	17.30*	°	22.30*	17.30*	°	22.30*	17.30*	°	22.30*	17.30*	°	22.30*
Chiusura seduta	12.00	15.00	16.30	17.30	°	23.45*	°	3.00	3.45	°	7.00	7.45	°	11.00	11.15	°	15.00	15.45	°	19.00
Esiti provvisori	12.42	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Esiti definitivi	12.55	15.30	17.00	21.45	#	0.15	2.15	#	4.15	6.15	#	8.15	10.15	#	11.45	14.15	#	16.15	18.15	#

** l'ora si riferisce al giorno D-9
* l'ora si riferisce al giorno D-1
° Si utilizzano le offerte presentate sul MSD1
Disciplina del dispacciamento

Figure 3: MI sessions scheduling

3. The MSD is the electricity market sub-phase in which Terna gets the necessary resources for monitoring and managing the grid. In this case Terna is the central counterpart, but the market is operated by GME on behalf of Terna itself. The accepted offers, unlike the other two subphases, are remunerated at the price offered (pay-as-bid method). The MSD is structured in two phases that are the MSD ex-ante and the MB (Balancing Market). Both of them are further developed in 6 sessions. During the MSD ex-ante, the resolution of infra-zonal congestions and energy reserve constitution occur, the sitting for bids submission in unique and occurs during the MSD1 and the results are known during the other sessions. The MB is instead needed for real time balancing issues. Many different services can be provided in the MSD, the most important ones are listed below:

- Resolution of congestions created after MGP and MI clearing. For the resolution of congestions problems, the enabled UA[7]s must provide a variation of their power injection up to their lower or higher limits.
- Secondary power reserve that is necessary to solve the unbalances between generation and load at the national grid boarders to restore the volumes exchanged and the frequency to their planned values.
- Spinning power reserve (tertiary power reserve) needed to restore the secondary reserve when it is used. A UA can be enabled to increasing reserve service, decreasing reserve service or both.

[7] An UA (Unità Abilitata) is a production unit enabled to provide ancillary services. To be enabled the unit must respect some constraints depending on the provided service.

- Replacement power reserve (tertiary power reserve) necessary to restore the previous one and face loads variations or long interruptions of generation groups. Also in this case, the UA can be enabled to provide increasing, decreasing services or both services.
- Balancing reserve that is used to ensure a perfect real-time balancing between generation and consumption.

However, these are not the only services needed for the safety and good quality operation of the national grid. There are other services that cannot be exchanged in the MSD but are automatically provided by power plants connected to the grid.

After this brief excursus about the current Italian electricity market structure, let us focus on the main theme of this section. As mentioned in the previous paragraph, a wide RES penetration in the electric system has a direct impact on the electricity market. To better visualise and understand this impact a very easy and strong indicator is the ratio between the volumes of energy exchanged in the MGP and the ones exchanged in the MSD, these quantities are represented in figure 4 (data available on Terna website and GME annual report 2019 [3], [4]):

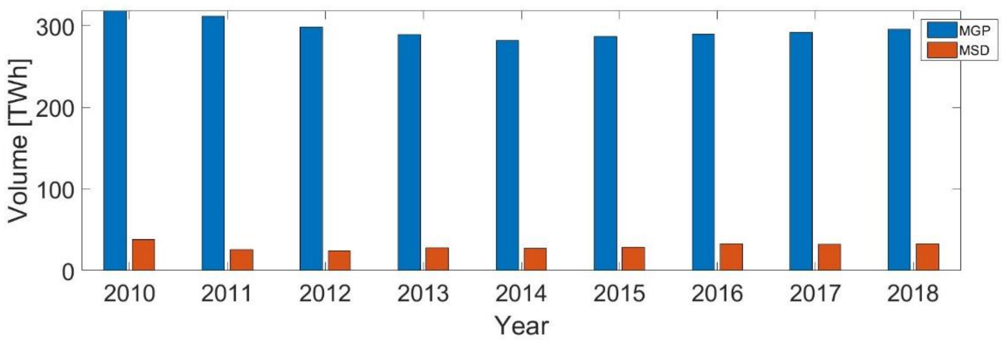

Figure 4: energy globally exchanged in the MGP and in the MSD

The figure above illustrates how the energy volumes exchanged in the MSD are slowly becoming more coherent with the ones exchanged in the MGP. In fact, the MSD to MGP ratio passed from the 8.3% in 2011 to the 11.2% in 2018. This clearly shows that the electricity market is moving from a planning phase to a real time structure. The increasing trend of the ratio is directly caused by a higher presence of renewable plant. In fact, being the RES mostly non-programmable sources, the power production is always characterised by a certain degree of uncertainty due to the accuracy of the predictions leading to a difficult participation to the MGP. This may cause two severe problems for the MSD. On the one hand, a high uncertainty about the produced power leads to higher reserve margins that must be constituted for ancillary services purposes, on the other hand a high RES penetration could also cause an economical issue. For example, when the production by renewable plants is high, thermoelectric plants work close to their minimum power level, in this condition the constitution of the needed power reserve results to be technically more difficult and consequently more expensive.

1.3 Towards the new TIDE

As mentioned at the very beginning of the chapter, changes in the electricity market dynamics must be sustained by an adequate legislation. For this purpose, in July 2019, ARERA[8] has published a document [5] containing the guidelines for the writing of the new TIDE[9]. In the document, a particular attention is given to two main aspects. First of all, the need of a reform of the Italian electricity market structure, secondly the importance of the cooperation between the different European countries regarding the ancillary services. These themes are respectively presented in the CACM rules [6] and in the Balancing rules [7] and are briefly explained in the following:

- The CACM rules (regulation UE 2015/1222) is directly related to the evolution of electric market towards the real-time as previously presented. The main theme of this document is the shift of the gate closure of the Infra-Day market just one hour before the real-time. This is in full agreement with the penetration of RES in the electric system since, the closer are the market ending session and the real-time, the more accurate will be the predictions of the produced power from renewable plants.
- The Balancing rules (regulation UE 2017/2195) are instead based on a more general aim. The main theme is that the TSOs will be able to exchange energy for balancing purposes at European level with the goal of creating a robust European

[8] ARERA is the Italian authority for the electric grid regulation.
[9] The TIDE (Testo Integrato del Dispacciamento Elettrico) is the document containing the rules for the electric dispatching.

electric grid through the adoption of a continental zonal model. This regulation also involves the presence of new figures such as the BSP and the BRP[10].

Furthermore, ARERA highlights the importance that both users and DSO[11]s will have when the new rules are applied. This is a complete revolution for the electricity market since also passive users will be able to actively participate to the market for the first time. It is also a fundamental step forward in order to achieve the switch from the current centralised approach to an innovative distributed one.

In this deeply changing scenario, Terna obviously plays a significant role since new resources able to provide at least the most important ancillary services must be clearly found. This is the reason why, starting from 2017, Terna opened the market to new participants through three main pilot projects in order to immediately find new resources to ensure the grid's safety and useful data for the writing of the new TIDE. However, Italy is still in an experimentation period since, according to the ARERA previsions, the new rules will be effective by the second half of 2021 or by the beginning of 2022.

[10] The definition and role of both BSP and BRP will be explained in the next chapter.
[11] The DSo is the Distribution System Operator, it is responsible for the correct management of distribution grids.

2. The UVAM pilot project

On May 5th 2017, through the Decree 300/2017/R/eel. [8], ARERA opened the ancillary services market to new participants. The above-mentioned Decree set a radical change for the market determining a switch from the historical concept of *relevant units* to the more innovative concept of *enabled units*. Thus, thanks to the market opening, MSD became attractive for the so-called UVA[12]s (Virtual Enabled Unit). Before the Decree, only two main players were involved in the electricity market: producers and consumers. However, during the last years, this distinction weakened since many generation units have been installed at distribution level, allowing final users to inject power into the grid. The main theme of the Decree is to exploit the concept of *Demand Response* leaving the loads free to adapt to the available generation and supply grid services. In this scenario the usual passive users become active participants of the market gaining the new role of *prosumers*. Figure 5 and figure 6 show the enabled users for MSD participation before and after the Decree, respectively.

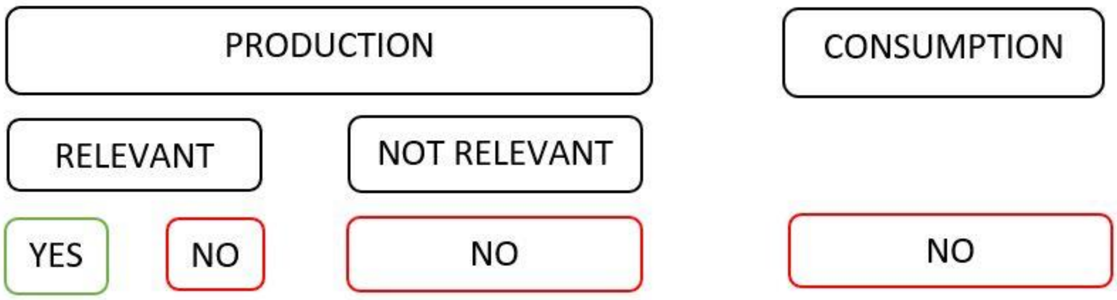

Figure 5: enabled MSD participants before the Decree

[12] UVA stands for Unità Virtuale Abilitata

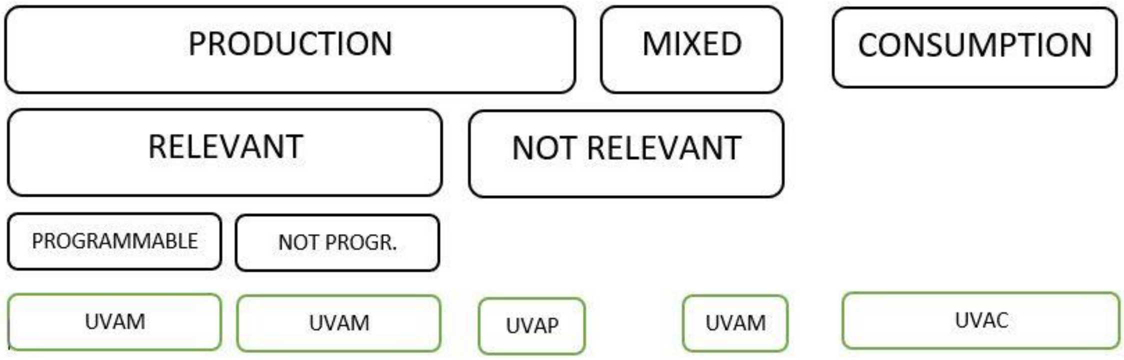

Figure 6: enabled MSD participants after the Decree

It is worth pointing out that for the first time ever also pure consumption units are considered active players in the market.

After the market opening, Terna instituted three main pilot projects to find new reliable resources for ancillary services supply:

- The UVAC pilot project started on May 2017. This project is focused on consumption units only, in fact, UVAC stands for Virtual Enabled Consumption Unit. The requirements for the UVAC creation and the rules for the forward ancillary services market participation are presented in the documents [9] and [10] respectively.
- In September 2017 also the UVAP pilot project started, it is focused on production units only. The acronym UVAP stands for Virtual Enabled Production Unit. The requirements for the UVAP constitution are described in [11].
- Finally, the UVAM pilot project started in September 2018, after the approval by ARERA with the Decree 422/2018/R/eel. [12]. This is the last pilot project launched by Terna that includes the presence of both consumption and production units. The acronym UVAM stands for Virtual Enabled Mixed Unit. The requirements for the UVAM creation are described in [13], while the rules for their market participation are presented in [14].

The UVAC and UVAP pilot projects were active until October 2018 since, by November 2018 they both became subsets of the UVAM. Therefore, this chapter is focused on the last one. However, before going deeper into details of the UVAM pilot project, it should be highlighted that two new figures have been introduced by the Decree [8], needed for a correct management of the aggregate. They are the BSP and the BRP, the same figures also introduced in the Balancing rules, as presented in the previous chapter:

- The BSP (Balancing Service Provider) is the effective owner of the UVA and responsible for the submitted offers of ancillary services to the grid operator. In the following, the BSP will be also called aggregator.
- The BRP (Balance Responsible Party) is a financial figure which is responsible for the imbalances of the units belonging to the UVA. In other words, the BRP is responsible for the correct execution of the dispatching orders sent by the grid operator to the UVA.

In the following section, the UVAM pilot project will be described in terms of requirements for the UVAM creation, services that it is possible to supply, obligations for the UVAM owner and service remuneration. In the end, the main results of the project will be shown.

2.1 Requirements for the UVAM constitution

Regarding the UVAM structure, two main types of UVAM are considered:

1. The so-called UVAM-A can be constituted by an aggregate of the following units:
    - Not relevant production units.
    - Consumption units, excluding the ones already involved in the interruptibility service.
    - Storage units, both stand alone or coupled with production or consumption units.
    - Relevant production units not mandatorily enabled to the MSD participation, that share the grid connection with other units such as consumption units, not relevant production units or storage units. However, the maximum power injection into the grid must be lower than 10MVA.
2. A UVAM-B can be constituted by one or more relevant production units that are not mandatorily enabled to the MSD participation and do not belong to the UVAM-A category. They can share the grid connection point with one or more not relevant production units, consumption units excluding the auxiliary services and/or storage units. In this case, the maximum power injection into the grid must be higher than 10MVA.

Independently from the UVAM type, other requirements, listed below, are needed for the UVAM creation:

- All the units must belong to the same aggregation perimeter. In the pilot project 15 geographical areas have been identified for the UVAM creation as illustrated in figure 7.
- Consumption units already involved in the Capacity Market, the so-called UCMC[13], are excluded.
- All the units that already have a dispatching contract with the AU[14] are excluded.
- For every unit belonging to the UVAM, a UPM (Peripheral Monitoring Unit) must be active to send measures to a remote control centre.
- For UVAM-B type, the power absorption of the consumption units must be at least the 50% of the produced one by the production units.
- Being the UVAM active in the electricity market, a new POD[15] must be constituted when the UVAM is created.

Figure 7: aggregation perimeters

[13] UCMC stands for Consumption Unit for the Capacity Market.
[14] AU stands for Acquirente Unico. It ensures the electric energy supply for all the consumers that have not chosen yet a supplier in the free market.
[15] POD stands for Point of Delivery.

Depending on the supplied services, the UVAM must respect the following power constraints:

- If the UVAM is only enabled for increasing power services, the maximum enabled power must be higher than 1MW and the minimum enabled power must be higher than 2kW.
- If the UVAM is only enabled for decreasing services the constraints are the same as before, but taken in absolute value.
- If the UVAM is enabled to both increasing and decreasing services, the maximum and the minimum enabled power must be higher than 1MW in absolute value.

2.2 Services

The UVAM can supply different ancillary services, as listed below:

- Congestions resolution, by accepting both increasing and/or decreasing offers. In particular, the UVAM must be able to perform the power modulation within 15 minutes from the receiving of the dispatching order. It must also be able to keep the modulation for at least 120 minutes.
- Increasing and/or decreasing replacement tertiary power reserve. In this case the UVAM must perform the power modulation within 120 minutes from the dispatching order and has to be able to keep the modulation for at least 480 minutes.
- Increasing and/or decreasing spinning tertiary power reserve. The modulation must be performed within 15 minutes from the order and the UVAM must be able to keep it for at least 120 minutes.
- Increasing and/or decreasing real time balancing. The UVAM must be able to perform the power modulation within 15 minutes from the dispatching order and must be able to sustain it for at least 120 minutes.

If more than the 50% of the modulating power of the UVAM is produced by renewable non-programmable plants, the UVAM cannot be enabled to supply increasing service of congestions resolutions, replacement tertiary power reserve and spinning tertiary power reserve.

2.3 Obligations for the UVAM owner

In order for the UVAM to be enabled, of course its owner must respect some obligations. The most important ones are listed below:

- The UVAM owner must communicate to the grid operator (Terna) the list of all the points involved in the aggregate. However, for each point, the owner must receive the approval of the UDS[16] responsible for that point that the BSP wants to involve in the UVAM (the BSP and the UDS can also be the same). Anyway, the approval can also occur in an implicit way if the UDS does not respond within 10 days from the request of the BSP.
- The aggregator has to communicate the technical data of all the units belonging to the aggregate. Terna can then validate or refuse the single points if some technical limitations are spotted.
- After the validation of the points, the BSP must prove to Terna that the UVAM is effectively able to correctly perform the power modulation.
- The BSP must constitute a physical control centre for the aggregate in order to receive the dispatching orders by Terna and execute them.
- The UVAM owner must communicate to the TSO the quarterly baseline of the aggregate. The baseline is the power program of the UVAM, and it is obtained by summing the power profiles of every point belonging to the aggregate. It is needed to Terna in order to verify that the dispatching order has been correctly executed.
- After the execution of a dispatching order, the aggregator must communicate to Terna the operation of any single unit used to perform the required modulation.
- The BSP must insert the offers on the GME platforms as already happens for the enabled participants to the MSD. In particular, the UVAM can perform at least one and up to three offers a day in the programming phase of the MSD that takes place the day before the delivery day (day D-1) both for increasing or decreasing services. While, at least one and up to four offers in the MB must be performed, both for increasing or decreasing services.

[16] UDS stands for User of Dispatching Services. It is the grid user involved in the dispatching activity.

2.4 Service remuneration

Regarding the offers' acceptance process and the remuneration, the rules are the same adopted for the relevant units already enabled to the MSD participation:

- Offers must respect the rules reported in the 4th chapter of the grid code [15].
- Regarding the accepted quantities and the remuneration during the programming phase of the ancillary services market, the rules are reported in the grid code-annex 22 [16].
- Regarding the accepted quantities and the remuneration during the real time phase of the MSD, the MB, the rules are reported in the grid code-annex23 [17].

Of course, Terna has to verify the correct execution of the dispatching orders, in case of a wrong execution of the order the aggregate is subjected to penalties. In particular, in case of UVAMs, two different penalties can be applied depending on the root-cause of the error during the service supply. Firstly, as happens for the already enabled units, a penalty is applied and must be paid to Terna if the despatching order is not completely respected. This happens when there is a mismatch between the accepted quantity and the effective supplied one. Then, an additional fine must be paid if the modulation is performed by using consumption units already enabled to the interruptibility service.

Besides the participation to the MSD, UVAMs can also participate to a forward ancillary services market. It is divided into auctions that, during the 2019, have been divided into an annual auction, three infra-annual auctions and twelve monthly auctions. This market has been introduced to ensure to Terna a certain modulating capacity for ancillary services purposes.

In order to participate to the forward ancillary services market, the aggregates must respect specific rules, in particular:

- The UVAM must present increasing offers for the real time balancing in the MB for at least 4 consecutive hours between 14:00 p.m. and 20:00 p.m. from Monday to Friday (Saturday and Sunday are excluded).
- Offers must be characterised by a price lower than a predetermined Strike Price. It has been set equal to 400 €/MWh during 2019.
- Offers must respect the rules reported in the 4th chapter of the grid code.

- The offered quantity has to be at least equal to the assigned capacity.

Two different remuneration are guaranteed. The variable remuneration which is the usual remuneration coming from accepted offers in the MSD where services are paid pay-as-bid following the rules reported in the 7th chapter of the grid code [18]. Moreover, for the pilot project period also a fixed remuneration is paid to the UVAM, it is independent from the acceptance of the presented offers and is given if the UVAM respects all the constraints listed above. This is a further incentive introduced to encourage the participation to the project. The fixed remuneration is computed daily with the equation (1) and it is earned through downward auctions starting from the value of 30000 €/MW/year.

$$daily\ fixed\ remuneration = \frac{fixed\ remuneration}{12 * m} \tag{1}$$

Where 12 is the number of months, and *m* is the number of days of the considered month. Anyway, some rules have to be respected to be able to gain the fixed remuneration:

- If the presented offers have a duration lower than four hours, then the remuneration is linearly reduced as shown in equation (2), while if the duration is lower than 2 hours the remuneration is not paid at all.

$$fixed\ remuneration = 30000 * \frac{duration\ of\ the\ offer}{4} \tag{2}$$

- If, during a month, offers are not presented for at least the 70% of the available days, the fixed remuneration is not paid for the entire month.

Finally, there are four cases in which the aggregate completely loses the right to participate to the forward ancillary services market:

- When for one sixth of the months, even if not consecutive, offers are not presented for at least the 70% of the available days.
- When, after the execution of a dispatching order, the UVAM does not supply at least the 70% of the energy requested by Terna for five consecutive days during a calendar year.

- If one or more production units belonging to the UVAM are involved in the Capacity Market.
- If one or more consumption units belonging to the UVAM are involved in the Capacity Market.

2.5 Pilot project results

In this paragraph the main results of the UVAM pilot project will be presented and analysed. They are available on the *Electricity Market Report 2019* [19] and are referred to the year 2019.

Last year Terna made available a modulating capacity of 1000 MW to be exploited by the UVAMs for the supplying of ancillary services. In particular, this capacity has been divided in two areas (see figure 8):

- 800 MW available for the Area A, comprehensive of northern and central-northern Italy.
- 200 MW available for the Area B, comprehensive of central-southern Italy, southern Italy, Sicily and Sardinia.

Figure 8: Area A and Area B

In October 2019, the available capacity has been almost saturated in both areas. In fact, the enabled UVAMs exploited the 97% of the 800 MW in the Area A and the 85% of the 200MW in the Area B. This means that the pilot project has been positively embraced in the whole country. The project involved a total of 156 UVAMs and 27

BSPs mainly located in the Area A, a BSP can also operate in both areas and the vast majority of the UVAMs were located in the northern area. Figure 9 and figure 10 illustrate the geographical location of aggregates and operators respectively.

Figure 9: geographical location of UVAMs

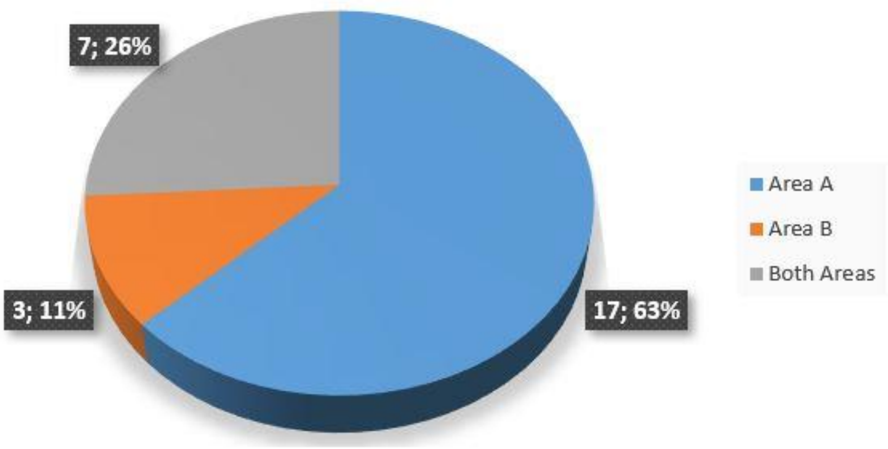

Figure 10: geographical location of the BSPs

Regarding the UVAMs typology, almost the 60% of them resulted to be constituted both by production and consumption units. Followed by the 23% constituted by only production units and the remaining 17% just by consumption units as shown in figure 11.

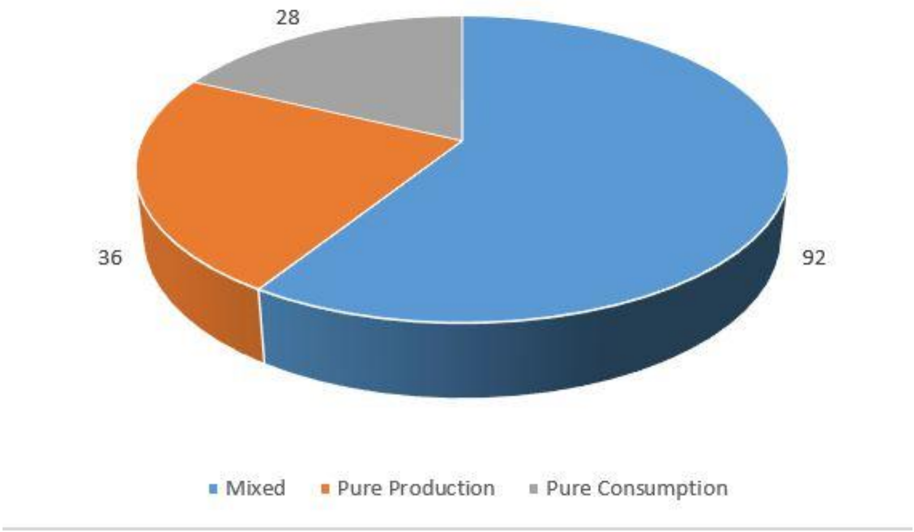

Figure 11: UVAMs constitution

The 38% of the UVAMs has been enabled for a modulating capacity ranging between 2MW and 5 MW. Just the 19% of them resulted to have a capacity higher than 10 MW, meaning that the majority of the involved UVAM were small size ones. Medium size UVAMs were also popular, since the 24% of them has an enabled power between 5 MW and 10 MW (figure 12).

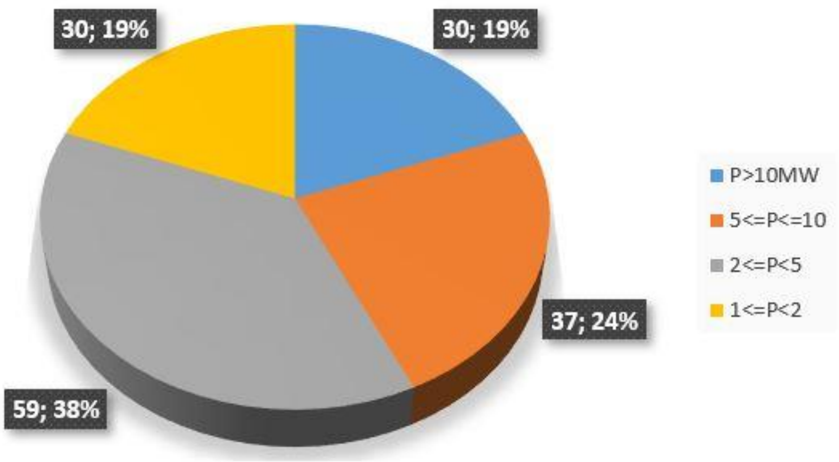

Figure 12: UVAMs enabled capacities

During 2019, the 85% of the accepted quantities has been characterised by a price lower than 100 €/MWh (figure 13). However, some offers have been accepted at prices close to the Strike Price (400 €/MWh). In fact, during the offers selection process the economic factor can be overcome for system's security reasons. A total of 556.5 MWh has been exchanged by the UVAMs in the period.

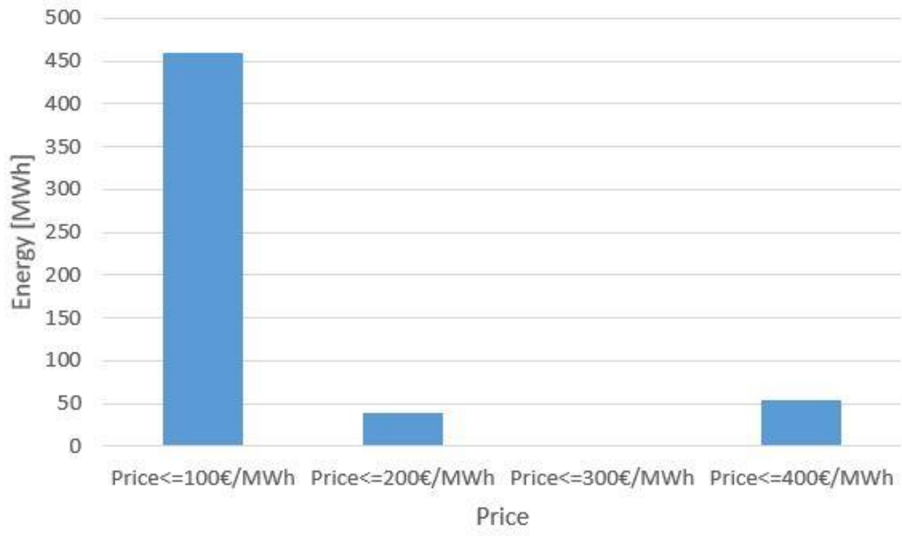

Figure 13: prices of the accepted quantities

UVAMs have generally been able to respect the dispatching orders sent by Terna. In fact, in the 67% of the cases at least the 70% of the accepted energy has been effectively provided. However, only in the 3% of the cases the dispatching order has been fully respected and in the 9% of the cases the order has not been executed at all as illustrated in figure 14.

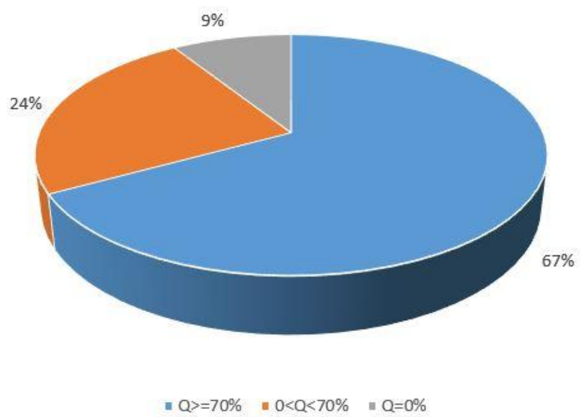

Figure 14: outcome of the dispatching orders

It is worth to notice that Italy is still in an experimental phase regarding the market opening. In fact, the potential that UVAMs can offer has not been exploited yet. During 2019, Terna only selected offers for increasing balancing services that represent the 5% of the submitted ones. This negative trend was mainly due to financial reasons since the submitted offers were characterised by very high prices close to the Strike Price reducing the possibility of being accepted since not competitive on the market. Therefore, data that are nowadays available do not allow to draw general conclusions about the full potential that UVAMs can give to the electricity market and to the electric grid more in general. Regarding the pilot project it is possible to conclude that it has been positively embraced by the operators in the whole country. In fact, the available capacity has been almost saturated in both Area A and Area B as presented at the beginning of the paragraph. Nevertheless, due to the very low numbers of accepted offers, the real benefits derived from the exploitation of UVAMs instead of the conventional thermoelectric power plants for the ancillary services supply is still unknown. However, even if the results of the pilot project are not exciting up to now, there is no doubt that UVAMs represent an interesting and innovative solution to face the deep changes that are occurring in Italy regarding the RES penetration and its impact on the electricity market. Moreover, it must be highlighted that the current legislation does not account for the presence of UVAMs for the ancillary services supply, so in future with a more suitable legislation it might be possible to observe a larger employment of such resources.

Nevertheless, Italian companies still show a high interest in UVAMs as proved by Enel X that, at the beginning of the year, launched an important project in this context. Enel X is the Enel business group focused on innovative products and digital solutions. The experimentation consists in the aggregation of residential storage systems in order to enable private users to participate to an active demand management through the UVAM aggregates. The trial will end at the end of the year and includes the participation of hundreds residential units in the provinces of Brescia, Bergamo and Mantua. Marco Gazzino, the Enel's Head of Innovation and Product Lab, during a press conference on the 14th January 2020 [20], expressed encouraging words about the project:

"The potential of this experimentation is enormous: there are thousands of residential batteries in Italy that will help ensure the stability of the power system. This is a milestone

for the Country on its path towards an increasingly sustainable energy model. The aggregation enables generation and storage plants distributed throughout the territory to participate in the network services market reserved until recently only to large production plants"

3. The optimization model for the supermarket

Thanks to the market opening, for the first time ever, consumption units are able to provide ancillary services since in the past only production plants were considered relevant and enabled to participate to the electricity market. Moreover, as presented in the UVAM pilot project results, a UVAM can be constituted only by consumption units. This is the main focus of this thesis work, more into details, the aim is to study the economic profitability of a supermarket's participation to the ancillary services market through the constitution of an aggregate fully composed by consumption units of the same type. In other words, the purpose is to analyse the economic benefits derived from an active dispatchable loads management. In particular, the supermarket is able to shift its electric load exploiting the thermal capacity of its refrigeration units represented by both freezers and fridges. In the following section the main characteristics of the studied case are illustrated and then the optimization algorithm developed is described into details.

3.1 Characteristics of the supermarket

The studied supermarket is located in Desenzano del Garda (BS), in northern Italy. The main characteristics of this supermarket are taken from [21], and they are briefly recalled here below.

It is an *all-electric supermarket* meaning that it interfaces with the electric grid for every kind of load fulfilment (see figure15).

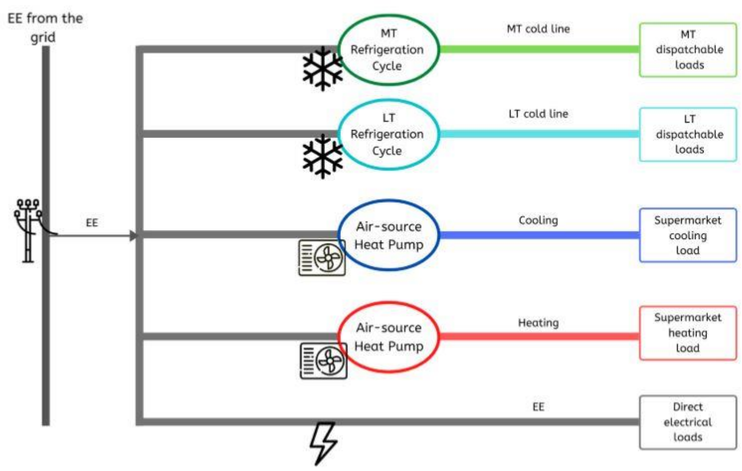

Figure 15: Supermarket-grid interface, picture from [21]

Figure 15 shows that the supermarket directly purchases energy from the electric grid that is needed to fulfil the loads. Electricity is then directly consumed by the electrical loads or converted in thermal energy for the fulfilment of the other loads. In particular, there are five types of loads:

- Direct electrical loads. These are represented by indoor and outdoor lights, elevators from the parking lot to the store, illumination for the display cabinets and others.
- Cooling and heating loads. Thermal comfort conditions for the people inside the supermarket are ensured by means of dedicated Air-Source Heat Pumps.
- MT and LT dispatchable thermal loads. Both LT and MT refrigeration cycles do not have to fulfil a specific energy demand, their aim is the correct conservation of food. These loads are assumed to be the ones that offer flexibility to the operation of the supermarket and are the ones that can be exploited to achieve the load shifting needed for the participation to the ancillary services market. The key point is that it is not necessary to keep the temperatures of fridges (MT) and freezers (LT) at a specific set point, but it is possible to let them change inside a suitable range for food conservation. In particular, it is assumed that the temperature of the MT loads can range between -2°C and 4°C while, the temperature of the LT loads is free to range between -26°C and -20°C.

The energy model for the loads and for the machines characterization has been developed in [21] where it is explained deeper into details how the electrical demand, the cooling demand, the heating demand, and the machines' COP curves have been developed.

After this brief presentation of the case study, now the focus is the presentation of the MILP optimization model that has been developed to compute the operation of the supermarket.

3.2 The MILP model

The complete MILP optimization model used for the optimization of the supermarket's operation is described in this section. However, it is worth to highlight that the model has been developed in [21], and it has been extended in this thesis work in order to account for the supermarket's participation to the ancillary services market. Specifically, the model has been written in the POLIMIP environment. POLIMIP is a novel modelling toolbox developed at Politecnico di Milano in 2019 to overcome the three main limits of YALMIP in modelling and solving MILP problems in MATLAB [22], the limits are:

a) The absence of a set-oriented syntax
b) The absence of full compatibility with the MATLAB API of the MILP solver
c) The absence of advanced functionalities in the MATLAB API of the MILP solver

A MILP model is structured by five main components that are the sets, the parameters, the variables, the constraints and the objective function. They are presented in the following with reference to the supermarket case study.

3.2.1 Sets

Sets represent the structure of the problem; all the other components of the model will be indexed on them. For this problem five sets have been identified:

- **Time**: it defines the time steps in which all the other components are computed, and it is identified through the letter T. T = {t_1, t_2, ……., $t_{simulation}$}.
- **Machines**: this set includes all the machines needed for the correct fulfilment of the loads and it is identified through the letter M. M = {LTC, MTC, HVACC, HVACH}. Where LTC and MTC are the machines that convert the electric power input into thermal power needed to keep the temperatures of the LT and MT dispatchable loads inside their ranges. HVACC and HVACH are the machines for the air conditioning of the supermarket. In particular, they have to fulfil the cooling and the heating demands respectively.
- **Dispatchable loads**: this set is constituted of the two thermal loads that offer flexibility to the operation of the supermarket, the set is identified through the letter D. D = {LT, MT}. Where LT and MT respectively represent the freezers and the fridges of the supermarket.

- **Operation**: this set is needed in order to separate the two main operative scenarios for the supermarket and it is identified through the letter O. O = {base, call}. The "base" scenario represents the everyday operation of the supermarket when it is involved in the UVAM. It represents a case in which the unit is able to supply the service, but the dispatching order is not sent by Terna. The "call" scenario is instead representative of the operation of the supermarket when a dispatching order is sent by Terna, so the service must be provided.
- **Goods**: they represent every form of energy and/or other valuable material involved in the energy system operation. The set is identified through the letter G. G= {EE, LTF, MTF, C, H}. Where EE is the electricity, LTF and MTF represent the thermal energy needed for the correct food conservation, C and H represent the cooling and heating energy needed to ensure thermal comfort conditions in the supermarket.

3.2.2 Parameters

Parameters are values known in advance that play an active role in the definition of the physic of the problem and are indexed on one or more sets. For this specific case, the parameters involved in the model are:

- in^{min}_i ; $i \in M$. It is the minimum input machine consumption of the machine *i* of the supermarket.
- in^{max}_i; $i \in M$. It is the maximum input machine consumption of the machine *i* of the supermarket.
- $m_{i,t}$; $i \in M$, $t \in T$. It is the input consumption per produced output of the machine *i*, at time *t*.
- q_i ; $i \in M$. It is the virtual input consumption of the machine *i* at null output.
- $Co\&mtime_i$; $i \in M$. It represents the O&M costs related to the time of the machine *i* operation.
- $Co\&mstart_i$; $i \in M$. O&M costs related to number of startups of the machine *i*.
- $Co\&minput_i$; $i \in M$. O&M costs related to the input consumption of the machine *i*.
- in^{up}_i; $i \in M$. It is the maximum input consumption increase in a single time step of the machine *i*.

- in^{down}_i ; i ϵ M. It is the maximum input consumption decrease in a single time step of the machine *i*.
- t^{up}_i ; i ϵ M. It is the minimum uptime value for the machine *i*.
- t^{down}_i ; i ϵ M. It is the minimum downtime value for the machine *i*.
- el^{cost}_t ; t ϵ T. It is the cost of the purchased electricity from the grid at time *t*.
- $demand_{t,k}$; t ϵ T, k ϵ G. It is the demand curve of good *k* at time step *t*.
- $temp^{max}_j$; j ϵ D. It is the maximum temperature that the dispatchable thermal load *j* can reach for the correct conservation of food.
- $temp^{min}_j$; j ϵ D. It is the minimum temperature that the dispatchable thermal load *j* can reach for the correct conservation of food.
- Cth_j ; j ϵ D. It is the thermal capacity of the dispatchable thermal load *j*.
- UA_j ; j ϵ D. It is the overall heat exchange coefficient of the dispatchable thermal load *j*.

3.2.3 Variables

Variables are quantities whose values are not known in advance and must be found by solving the optimization problem. They can be integer, binary or continuous and are indexed on one or multiple sets. For this specific problem, the considered variables are:

- $z_{i,t,o}$; i ϵ M, t ϵ T, o ϵ O. This is the machine status variable. It is a binary variable and when it is equal to 1 the machine *i* is running at time *t* during the operation *o*, while when it is equal to 0 the machine is off.
- $in_{i,t,o}$; i ϵ M, t ϵ T, o ϵ O. It is the input consumption of the machine *i* at time *t* during the operation *o* and is a non-negative, continuous variable.
- $gen_{i,t,o}$; i ϵ M, t ϵ T, o ϵ O. Is the generated output of the machine *i* at time *t* during the operation *o* and is a non-negative, continuous variable.
- $pgrid_{t,o}$; t ϵ T, o ϵ O. It is the energy purchased from the electric grid at time *t* during the operation *o*, is a non-negative continuous variable.
- $\delta^{on}_{i,t,o}$; i ϵ M, t ϵ T, o ϵ O. This is the startup variable. It is a binary variable that is equal to 1 if the machine *i* has been turned on at the time *t*, during the operation *o*.

- $\delta^{off}_{i,t,o}$; i ϵ M, t ϵ T, o ϵ O. This is the shut down variable and is the opposite of the previous one. It is a binary variable that is equal to 1 if the machine *i* has been turned off at time *t*, during the operation *o*.
- $temp_{j\ t,o}$; j ϵ D, t ϵ T, o ϵ O. This variable is the temperature of the dispatchable thermal load *j* at time *t* during the operation *o*. It is a continuous variable.
- φ_t ; t ϵ T. This is the market variable. It is a binary variable and it is equal to 1 in the time-steps *t* in which the UVAM submits an offer in the MSD, meaning that when $\varphi_t = 1$ the supermarket must be able to perform the power modulation if a dispatching order is sent by Terna.

3.2.4 Constraints

Constraints are the components of a MILP model that really define the physical behaviour of the system. They are constituted by equations or inequalities, based on feasible hypotheses, that must be respected in order to limit the possible values of the variables. The right writing of the constraints is crucial to obtain a meaningful solution of the problem. In this case study, the considered constraints are:

- *Maximum machines input consumption*. It sets the maximum machines consumption at every time step and for both the considered operating scenarios.

$$in_{i,t,o} \leq z_{i,t,o} * in^{max}{}_{i} \quad \forall\, i \in M, t \in T, o \in O \tag{3}$$

- *Minimum machines input consumption*. This constraint sets the minimum machines consumption at every time step for both the considered operating scenarios.

$$in_{i,t,o} \geq z_{i,t,o} * in^{min}{}_{i} \quad \forall\, i \in M, t \in T, o \in O \tag{4}$$

- *Machines generation curve*. This constraint defines the relationship between the consumed input and the generated output of every machine, at every time step and for both the operating scenarios. The curves have been approximated with straight lines (figure 16).

$$in_{i,t,o} = z_{i,t,o} * q_i + gen_{i,t,o} * m_{i,t} \quad \forall\, i \in M, t \in T, o \in O \tag{5}$$

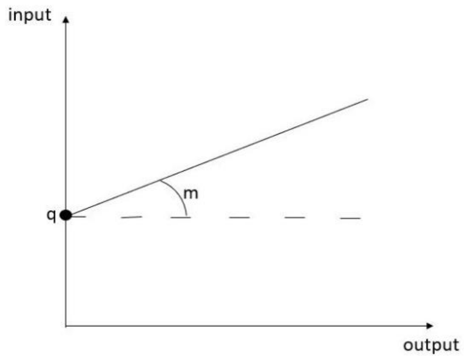

Figure 16: linear generation curve of the machines

- *Loads balances*. In this case two sub-balances must be considered. One for the non-dispatchable loads and one for the dispatchable thermal loads.
    - Regarding the non-dispatchable loads, they are characterised by a specific demand that has to be fulfilled. In particular, two balances have been written: equation (6) that is the electric balance and equation (7) that represents the heating and cooling balances. In the following equations, B_k is the sub-set of the machines that consume the good *k*, and M_k is the sub-set of the machines that produce the good *k*.

$$\sum_{i \in Bk} in_{i,t,o} + demand_{t,k} = pgrid_{t,o} \quad \forall\, t \in T, o \in O \tag{6}$$

$$demand_{t,k} = \sum_{i \in Mk} gen_{i,t,o} \qquad \forall\, t \in T, o \in O \tag{7}$$

    - The dispatchable thermal loads are not characterised by a specific energy demand. In this case the aim of the machines is to keep the food locations inside suitable temperature ranges. The thermal behaviour of the loads is expressed by the differential equation (8), where the exiting thermal power is due to the heat exchange with the external ambient of the supermarket while, the entering thermal power is represented by the output generated by the machines. It is then possible to split the variables and integrate the equation neglecting the time dependence of the refrigeration units' temperature on time between two consecutive time steps. In this way equation (9) is obtained and it is the one considered in the model. In this case, the only machines considered are the ones generating the good *k*.

$$C\frac{dT}{dt} = \sum(Q^{\leftarrow} - Q^{\rightarrow}) \tag{8}$$

$$Cth_j\left(temp_{j,t-1,o} - temp_{j,t,o}\right) = UA_j\left(T_{amb} - temp_{j,t,o}\right)\Delta t - \\ - \textstyle\sum_{i\in Mk} gen_{i,t,o}\,\Delta t \qquad \forall\ t \in T, o \in O, j \in D \tag{9}$$

- *Startup variable constraints*. They are introduced to induce the right behaviour of the startup variable.

$$\delta^{on}{}_{i,t,o} \geq z_{i,t,o} - z_{i,t-1,o} \qquad \forall\, i \in M, t \in T, o \in O \tag{10}$$

$$\delta^{on}{}_{i,t,o} \leq \frac{z_{i,t-1,o} - z_{i,t,o}}{2} \qquad \forall\, i \in M, t \in T, o \in O \tag{11}$$

- *Shut down variable constraints*. They are introduced to induce the right behaviour of the shut down variable.

$$\delta^{off}{}_{i,t,o} \geq z_{i,t-1,o} - z_{i,t,o} \qquad \forall\, i \in M, t \in T, o \in O \tag{12}$$

$$\delta^{off}{}_{i,t,o} \leq \frac{z_{i,t,o} - z_{i,t-1,o}}{2} \qquad \forall\, i \in M, t \in T, o \in O \tag{13}$$

- *Maximum ramp up rate*. This constraint is necessary to avoid that the machine goes from a low load to a high one in a small amount of time.

$$in_{i,t,o} - in_{i,t-1,o} \le in^{up}{}_i + in^{max}{}_i\left(1 - z_{i,t,o}\right) \qquad \forall\, i \in M, t \in T, o \in O \tag{14}$$

- *Maximum ramp down rate*. It is the opposite of the previous one, and it is needed to avoid that the machine goes from a high load to a too low one in a small amount of time.

$$in_{i,t-1,o} - in_{i,t,o} \le in^{down}{}_i + in^{max}{}_i\left(1 - z_{i,t,o}\right) \quad \forall\, i \in M, t \in T, o \in O \tag{15}$$

- *Maximum startup rate*. The constraint is needed to avoid that the machines goes from a null load to a too high one when it is switched on.

$$in_{i,t,o} - in_{i,t-1,o} \le in^{up}{}_i + in^{max}{}_i\left(1 - \delta^{on}{}_{i,t,o}\right) \quad \forall\, i \in M, t \in T, o \in O \tag{16}$$

- *Minimum uptime*. Once the machine is on, it cannot be turned off within a few time steps.

$$\sum_{t}^{t^{up}{}_i} z_{i,t,o} + \left(1 - \delta^{on}{}_{i,t,o}\right)t^{up}{}_i \ge t^{up}{}_i \qquad \forall\, i \in M, t \in T, o \in O \tag{17}$$

- *Minimum downtime*. Once the machine is turned off, it cannot be switched on within a few time steps.

$$\sum_{t}^{t^{down}{}_i} (1 - z_{i,t,o}) + (1 - \delta^{off}{}_{i,t,o})t^{down}{}_i \ge t^{down}{}_i \quad \forall\, i \in M, t \in T, o \in O \tag{18}$$

- *Dispatchable loads maximum temperature*. The dispatchable thermal loads temperatures do not have to exceed their maximum value.

$$temp_{j,t,o} \le temp^{max}{}_j \qquad \forall\, j \in D, t \in T, o \in O \tag{19}$$

- *Dispatchable loads minimum temperature*. The dispatchable thermal loads temperatures do not have to be lower than their minimum values.

$$temp_{j,t,o} \geq temp^{min}{}_{j} \qquad \forall\, j \in D, t \in T, o \in O \tag{20}$$

- *Temperature cyclic constraint*. Since the operation of the supermarket is analysed in four typical days, as it will be better explained in the next chapter, this constraint is necessary to ensure the continuity of the temperature behaviour between consequent days.

$$temp_{j,t=1,o} = \; temp_{j,t=end,o} \quad \forall\, j \in D, t \in T, o \in O \tag{21}$$

3.2.5 UVAM constraints

The constraints concerning the supermarket participation to the UVAM are presented in the following. These constraints are the real core of this thesis and have been written for all the machines. However, it is worth to highlight that they are only active for the machines that regulate the temperatures of the dispatchable thermal load. In fact, the operation of the machines needed for the supermarket heating and cooling is independent from the UVAM participation to the ancillary services market and remains unchanged during the “base” and “call” scenarios. Moreover, since the UVAM is assumed to be composed by consumption units of the same type, it is imposed that every supermarket belonging to the aggregate must respect the same constraints and perform the same power modulation for the supply of the service.

- *Market variable constraints*. The following constrains are introduced to set the right behaviour of the market variable φ_t. More specifically, the variable must be equal to 1 for four consecutive hours during the market window that goes from 14:00 p.m. (q_i) to 20:00 p.m. (q_f) according to the rules for the UVAM market participation illustrated in the previous chapter. Equations (25) and (26) ensure that the four hours are effectively consecutive. During the first two hours of the market window the condition $\varphi_{t-1} = 1$ and $\varphi_t = 0$ is indeed not allowed while, the opposite is imposed for the last two hours. Equation (25) is written only for the first two hours of the market window because it is assumed that when a dispatching order is sent by the TSO, it lasts for four consecutive hours. Hence, the market variable is for sure equal to 1 from 16:00 p.m. to 18:00 p.m.

$$\varphi_t = 0 \quad \forall t \in [1;\ q_i - 1] \tag{22}$$

$$\varphi_t = 0 \quad \forall t \in [q_f + 1; end] \tag{23}$$

$$\sum_t \varphi_t = 16 \quad \forall t \in T \tag{24}$$

$$\varphi_t \geq \ \varphi_{t-1} \ \ \forall t \in [q_i;\ q_i + 7] \tag{25}$$

$$\varphi_t \leq \ \varphi_{t-1} \ \ \forall t \in [q_i + 16;\ q_f] \tag{26}$$

- *Operation constraints before the market window.* Since the outcome of the dispatching order is made known 15 minutes before the real time, the operation of the machines, before the market window, must be the same in the "call" and in the "base" operating scenarios.

$$in_{i,t,o=1} = in_{i,t,o=2} \quad \forall i \in M, t \in [1; q_i - 1] \tag{27}$$

- *Operation constraints for the first four hours of the market window.* During the first four hours of the market window, when the market variable is equal to 1, a despatching order can be received from Terna. In order to correctly execute it the overall electric consumption of the unit must be reduced by a quantity Δp in the "call" operating scenario with respect to the electric consumption of the "base" one, as expressed in equation (28). However, in the first two hours of the market window, it is possible that the dispatching order is not sent by the TSO (market variable equal to 0), meaning that the machines' operation has to remain unchanged in the two operating scenarios. That is the reason why in the equations (29) and (30) a big enough quantity M is used to ensure that such constraints become trivial if the market variable is equal to one.

$$pgrid_{t,o=1} = pgrid_{t,o=2} - \Delta p * \varphi_t \quad \forall t \in [q_i; q_i + 15] \tag{28}$$

$$in_{i,t,o=2} \leq in_{i,t,o=1} + M * \varphi_t \qquad \forall i \in M, t \in [q_i; q_i + 7] \qquad (29)$$

$$in_{i,t,o=2} \geq in_{i,t,o=1} - M * \varphi_t \qquad \forall i \in M, t \in [q_i; q_i + 7] \qquad (30)$$

- *Operation constraints for the last two hours of the market window.* In the last two hours of the market window, when the market variable is equal to 1, the service must be supplied. Thus, the electrical consumption of the supermarket in the "call" operating scenario must be reduced by a quantity equal to Δp with respect to the consumption of the "base" operating scenario. Instead, when the service has been provided, and the market variable is null, the operation of the supermarket does not have to be bound and the solver can find the optimal operation needed to bring the dispatchable thermal loads' temperatures back to the values they had at the beginning of the day. A big enough quantity M is used to ensure the correct behaviour of these constraints.

$$pgrid_{t,o=2} \leq pgrid_{t,o=1} - \Delta p * \varphi_t + M(1 - \varphi_t) \qquad \forall t \in [q_i + 16; q_f] \qquad (31)$$

$$pgrid_{t,o=2} \geq pgrid_{t,o=1} - \Delta p * \varphi_t - M(1 - \varphi_t) \qquad \forall t \in [q_i + 16; q_f] \qquad (32)$$

3.2.6 Objective function

The goal of an optimization model is to minimize or maximize a certain value, the so-called objective function. In this case the objective function represents the total operating costs of the supermarket and it is composed by four terms, namely:

- The cost of the electricity purchased from the grid.
- The O&M costs related to the time of operation of the machines.
- The O&M costs related to the number of startups of the machines.
- The O&M costs related to the input consumption of the machines.

The goal is of course to minimize it in order to find the optimal operation that allows the supermarket to participate to the ancillary services market.

$$\sum_o \{ \sum_t [pgrid_{t,o} * el_t^{cost} + \sum_i (Co\&mtime_i * z_{i,t,o} + Co\&mstart_i * \delta_{i,t,o}^{on} + Co\&minput_i * in_{i,t,o})] \} * \alpha_o \quad (33)$$

Where α_o represents the probability given to the occurrence of the o operating scenario. In particular, in this work, two operating scenarios are considered: the “base” and the “call” one. Whenever a dispatching order is sent by the TSO to the UVAM, the “call” scenario occurs, otherwise the units follow the “base” operating scenario. Thus, the probabilities given to the scenarios are complementary ($\alpha_{o=base} = 1 - \alpha_{o=call}$).

Additionally, equation (33) shows that the remuneration derived from the supply of the service is not considered in the objective function of the model because, as it will be better explained in the next chapter, both the power modulation performed by the units and the price offered for the service are parameters. Hence, the presence of the remuneration does not influence the solution of the optimization, but it just represents an offset for the objective function.

4. Results analysis and conclusions

The supermarket is able to offer increasing real time balancing services in the MSD by reducing its electricity consumption whenever a dispatching order is received from the TSO, this is the main way for a consumption unit to offer ancillary services. The goal of this analysis is to study the profitability, for the supermarket, to participate to the ancillary services market as a consumption unit that is part of a UVAM constituted by units of the same type. In particular, three main cases are considered, namely:

1) *no UVAM case*. The supermarket does not participate to the MSD and the operating flexibility ensured by the active management of the dispatchable thermal loads is exploited to minimize the operating costs. This case sets a lower bound of the supermarket's costs and all the cost differences computed in the next cases are referred to this one.
2) *UVAM "no call" case*. The aim of this case is to find the minimum operating costs that allow the supermarket's participation to the MSD, without accounting for the costs derived from a dispatching order execution. This case provides the minimum "base" operating scenario cost that the supermarket has to sustain in order to be able to submit an offer on the market for increasing balancing services. The probability α_o given to the "call" scenario in the objective function of the model is null. The operation of the supermarket is studied for different power modulations Δp performed by the unit, namely: 50kW, 100kW, 125kW, 200kW, 250kW. In this way it is possible to relate the operating costs of the "base" scenario to the number of units belonging to the aggregate. The UVAMs' overall modulating capacity is assumed to be equal to 1MW, meaning that the number of units belonging to the UVAM ranges between 20 (each unit performs a 50kW power modulation) and 4 (every unit performs a 250kW power modulation).
3) *UVAM case*. It is divided in two sub-cases:

- *The UVAM's architecture analysis*. In this sub-case the statistical weight α_o given to the "call" scenario in the objective function is equal to 5%. This case is representative of the UVAM pilot project results since, as presented in Chapter 2, during the 2019 the dispatching orders sent by Terna were the 5% of the overall number of the submitted offers. An annual economic assessment of the profitability of the supermarket's participation to the MSD is carried out accounting for different frequencies of the days in which the unit is effectively called to provide the service. This annual analysis is iterated for all the above-mentioned power modulations performed by the unit in order to find the UVAM's configuration (i.e. the number of units) that ensure the highest income.

- *"call" probability analysis.* A sensitivity analysis is carried out accounting for different statistical weights α_o of the "call" scenario in the objective function of the model. This analysis shows the impact of the probability given to the operating scenarios "base" and "call" on the solution of the optimization solution. However, the analysis is done only for the most profitable UVAM's configuration.

In this thesis work, an analysis on the size of the UVAM is not needed since the work is focused on the asset owner point of view. Hence, once the power offered by the single units is set, revenues are independent from the overall modulating capacity of the whole aggregate since the fixed remuneration is specific to the power of the UVAM [€/MW/year] and the variable remuneration is specific to the energy provided [€/MWh]. Nevertheless, the size of the UVAM is a key parameter that should be accounted in an analysis carried out from the BSP point of view. In fact, on the one hand the only costs that units have to sustain for their participation to the aggregate are the modulating costs, on the other hand, the BSP must sustain other kind of costs, the most important ones are:

- The platform for the communication with Terna, through this platform the BSP is able to receive the dispatching order from the TSO and Terna can verify its correct execution in terms of quantity supplied and time needed to perform the requested modulation.
- The centralised control centre for the units' management. When a despatching order is sent by the TSO, the BSP must provide the service by managing some of the units belonging to the aggregate in order to supply the service.
- The UPMs. According to the UVAM pilot project rules regarding the obligations of the BSP, every unit must have a UPM that measures the technical specifications of the unit and sends them to the centralised control centre.

However, only the last one depends on the number of units belonging to the aggregate, and consequently on the size of the UVAM while, all the others, only depend on the aggregation process. Therefore, from the BSP point of view, the optimal configuration, given a certain size of the UVAM, is to manage the lowest possible number of units. In other words, the aggregate has to be constituted by a few units that are able to perform large power modulations.

Finally, in order to better understand the results, it is worth to point out the other hypotheses at the basis of the work.

- The operation of the supermarket is analysed in four typical days, each of them representative of a season. For every typical day, the daily profiles of the electricity cost, the non-dispatchable loads' demands, and the COP of the machines are generated by means of a traditional k-means algorithm from the annual profiles developed in [21]. Considering that the four typical days are used to simulate the annual operation of the supermarket, as better explained in section 4.3.1, equation (21) is introduced in the MILP model in order to ensure the continuity of operation between two subsequent days.
- Regarding the economic assessment of the supermarket participation to the ancillary services market, a price of 50 €/MWh has been used and kept constant throughout the year. This price was selected starting from the MSD market analysis presented in [23]. According to that analysis this price ensures a high probability that an offer on the ancillary services market is accepted by Terna in northern Italy. In particular, the analysis shows that with a price of 50 €/MWh the probability that a dispatching order is effectively sent by the TSO is equal to 90% (figure 17). This is aligned with the results of the UVAM pilot project since, as presented in chapter 2, the 85% of the accepted quantities were characterised by a price lower than 100 €/MWh.
- Since data about the effective duration of the dispatching orders sent by Terna to the UVAMs have not been found, it is assumed that the duration of the order is the same of the submitted offer (4 hours).

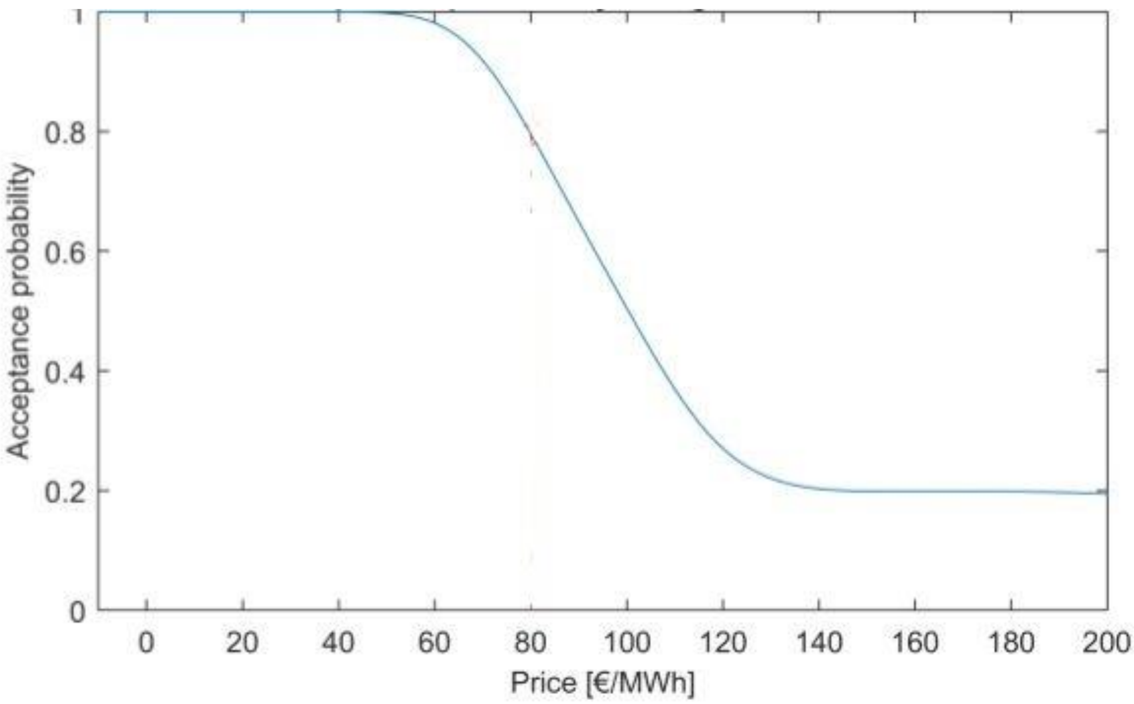

Figure 17: probability for an offer of being accepted, NORD, picture from [23]

- The revenues derived from the MSD participation of the UVAM must be divided between the BSP and the asset owners of the different units. In this work it is assumed that the 60% of both fixed and variable remunerations goes to the owners of the supermarket and the 40% to the aggregator. This distribution is representative of a so-called *client driven BSP* that already has relations with the asset owners and can hold a huge portion of the profits. The other main business model is the so-called *technology driven BSP*. In this case the aggregator has an easy access to the technological part of the aggregate comprehensive of the platform for the communication with Terna, the control centre for the management of the units etc. Anyway, this kind of BSP has not relations with the asset owners and usually has to give them a higher part of the revenues, typically the 80%, to convince them to be part of the aggregate. It is important to emphasize that the share of the revenues between the BSP and the units is not part of the UVAM pilot project rules, and it is chosen case-by-case by the aggregator and the units.

4.1 No UVAM case

In this case, the scheduling plan is optimized with the only objective of operating costs minimization, without the constraint of being able to supply the service in the MSD. So, this case represents the lower bound for the operating cost of the supermarket and the cost differences computed for the “base” and the “call” operating scenarios in the next cases are referred to this one. From figure 18 to figure 21, it is represented the operation of the supermarket in the four considered typical days in terms of electric input consumption and dispatchable loads’ temperatures. In particular, in the figures three plots are shown, namely:

- The top plot shows the electrical input consumption, expressed in kW, of the machines needed for the dispatchable loads’ temperatures management (the LTC and the MTC). In this thesis work it is assumed that dispatchable thermal loads are the only ones able to give flexibility to the supermarket’s operation while, the machines for the air conditioning have to fulfil specific heating and cooling demands. Thus, the operation of the HVACC and the HVACH is independent from the participation to the MSD, so it is not illustrated in the figures.
- The second plot shows the LT dispatchable load’s temperature behaviour. It is assumed that this temperature can range from -26°C to -20°C.
- The third plot illustrates the MT dispatchable lead’s temperature. It is assumed that this temperature can range from -2°C to 4°C.

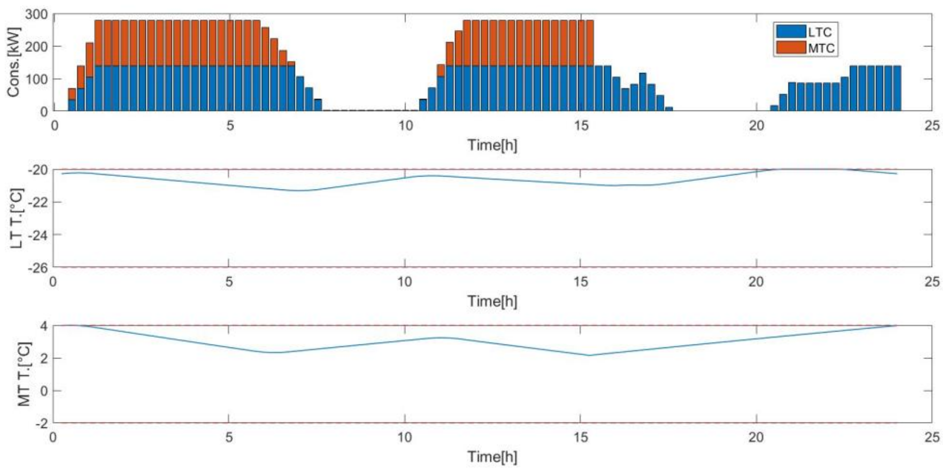

Figure 18: Autumn day, no UVAM case

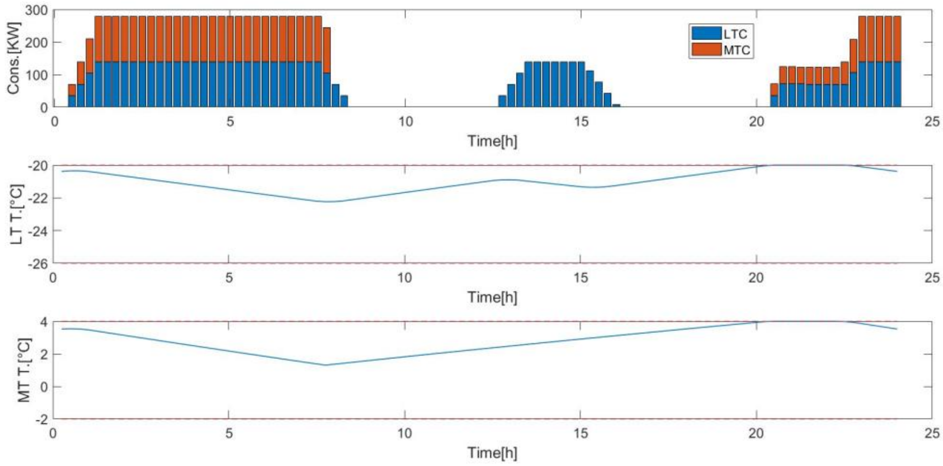

Figure 19: Winter day, no UVAM case

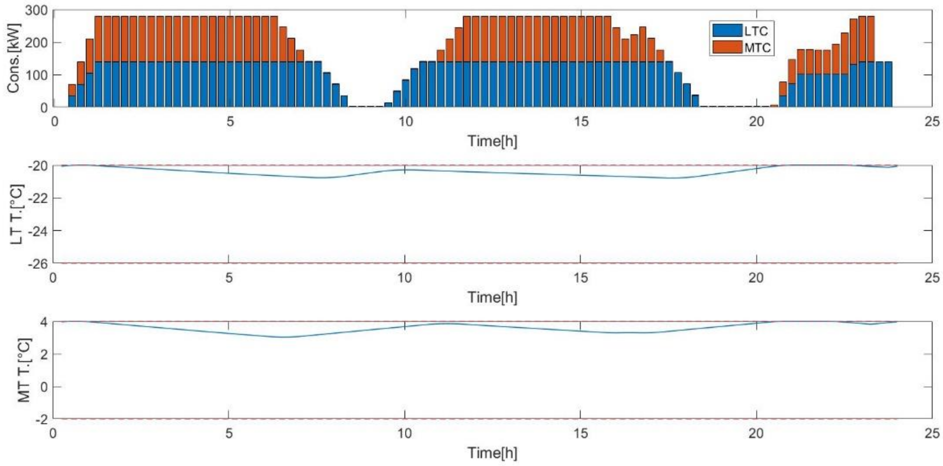

Figure 20: Summer day, no UVAM case

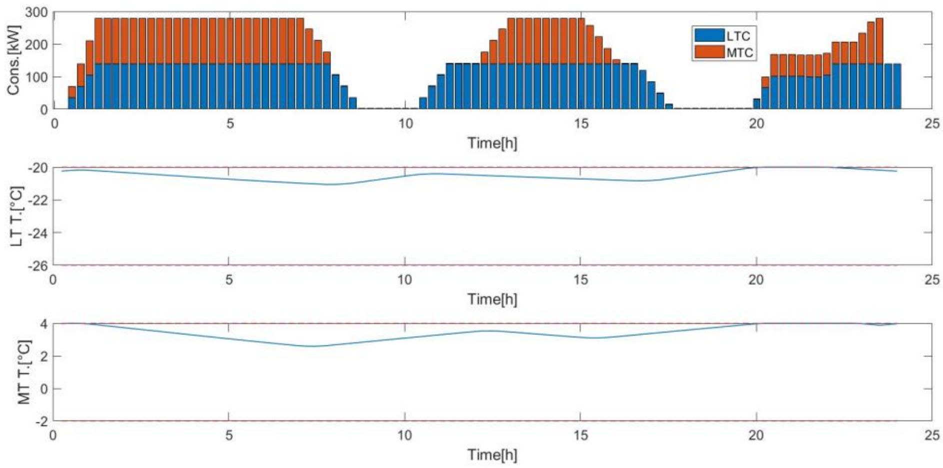

Figure 21: Spring day, no UVAM case

The figures show that the optimized management of the dispatchable thermal loads leads to high temperatures of both the LT and the MT loads in order to minimize the thermal losses with the external supermarket ambient. In fact, only the upper semi band of variation is exploited since the lowest LT and MT temperatures are observed during the winter typical day and are about -22.5°C and 1°C, respectively.

Nevertheless, this operation does not allow to submit offers in the MSD observing the rules established in the UVAM pilot project. During the market window, from 14:00 p.m. to 20:00 p.m., the electric input consumption of the machines is indeed quite low, especially during the winter season, thus it cannot be further reduced to respect a hypothetical dispatching order. Moreover, the UVAM must submit offers for increasing balancing services for at least four consecutive hours.

Finally, Table 4, shows the operating cost of the supermarket for the four typical days considered.

Typical day	Operating cost [€/day]
Autumn	579.25
Winter	478.91
Summer	726.14
Spring	643.67

Table 4: Typical days operating costs, no UVAM case

The Summer typical day is the one characterised by the highest operating cost. This is mainly due to the high cooling demand that characterises such season leading to high consumptions of the air-cooling system. Moreover, also the electrical input consumption of the MTC and the LTC machines is quite high during summer, this will be better explained in section 4.2.

4.2 UVAM “no call” case

The aim of this case is to provide the minimum cost increase that the asset owner of the supermarket has to sustain in order to be able to submit increasing balancing offers on the MSD without considering the economic effect related to a dispatching order sent by the TSO. For this purpose, the statistical weight given to the “call” operating scenario in the objective function of the MILP model is null, and, consequently it is assumed that the “base” operating scenario has a 100% probability to occur. Hence, this case is the one characterised by the minimum cost differences between the “base” operating scenario and the *no UVAM case*. From Table 5 to table 9, the daily cost increase of both the considered operating scenarios are reported. However, it must be highlighted that the “call” operating scenario is not optimized being its weight in the model null and the economic impact of the execution of a dispatching order will be analysed in the next cases.

For every typical day, the daily cost differences are computed for five different power modulations performed by the supermarket. This is done to highlight the dependency of the operating cost of the “base” scenario on the number of units belonging to the aggregate. In this thesis work, it is in fact assumed that the UVAM is composed by many supermarkets of the same type and that the overall modulating capacity of the aggregate is 1MW. This means that the modulation Δp performed by the single unit is strictly related to the number of supermarkets belonging to the UVAM. In particular, the power modulations considered are: 50kW, 100kW, 125kW, 200kW, 250kW, meaning that the number of units ranges from 4 to 20 in order to reach the overall modulating capacity of the aggregate.

1. Autumn typical day

Power modulation [kW]	Cost increase “base” [€/day]	Cost increase “call” [€/day]
50	0.074	22.87
100	0.31	19.70
125	0.64	17.50
200	2.69	18.82
250	3.8	17.46

Table 5: Autumn day, daily cost increase, UVAM “no call” case

2. Winter typical day

Power modulation [kW]	Cost increase "base" [€/day]	Cost increase "call" [€/day]
50	0.44	20.82
100	1.25	34.22
125	1.72	34.65
200	3.93	20.60
250	5.62	15.33

Table 6: Winter day, daily cost increase, UVAM "no call" case

3. Summer typical day

Power modulation [kW]	Cost increase "base" [€/day]	Cost increase "call" [€/day]
50	0.003	20.27
100	0.053	21.82
125	0.09	19.54
200	0.49	15.82
250	0.76	15.41

Table 7: Summer day, daily cost increase, UVAM "no call" case

4. Spring typical day

Power modulation [kW]	Cost increase "base" [€/day]	Cost increase "call" [€/day]
50	0.098	17.63
100	0.26	16.35
125	0.75	19.57
200	2.29	18.92
250	4.91	21.25

Table 8: Spring day, daily cost increase, UVAM "no call" case

The Summer typical day is the one characterised by the lowest cost increase of the "base" scenario, with respect to the *no UVAM case*, for all the considered power modulations. In fact, by looking at figure 20, it is possible to notice that the electricity consumption of the machines for the dispatchable thermal loads' management is quite high for a large portion of the market window. Hence, the *no UVAM* operation of the supermarket in such season is almost suitable to submit an offer on the MSD even for a high power modulation. Contrarily, the Winter typical day *no UVAM* operation (figure 19) is not suitable to provide increasing balancing services since, during the market window, the MTC machine in turned off and the LTC one has a low electric input consumption for a few hours. These trends are due to the dependency of the COPs of the machines on the external ambient temperature. In particular, the higher is the external temperature, the lower are the COPs of the refrigerating cycles, meaning that during the hot seasons a higher input consumption is needed to regulate the temperatures of the dispatchable thermal loads. This trend, coupled to a higher cooling demand, leads to higher absolute operating costs during Summer and Spring.

As expected, the cost increase of the "base" scenario is directly proportional to the power modulation performed by the supermarket. In fact, in order to offer a high power modulation for increasing balancing services, the electric input of the machines results to be high during the market window that, being in the central hours of the day, is characterised by a high energy price.

Finally, the tables above show that the cost increase of the "call" operating scenario has not a precise dependency on the power modulation performed by the UVAM. This peculiar trend was also expected since, as explained at the beginning of this section, the operation in the "call" scenario is not optimized being its probability in the objective function null.

The operation of the supermarket in the four typical days considered is shown in the next figures in terms of electric input consumption of the machines and dispatchable loads' temperatures. Only the operations of the supermarket performing a power modulation of 50 kW and 250 kW are illustrated. In particular, each figure is divided in four plots:

- The top plot illustrates the machines' electric input consumption (expressed in kW) in the "base" operating scenario. The MTC machine is represented in orange and the LTC one in blue.

- The second one shows the machines' electric input consumption (expressed in kW) in the "call" operating scenario. The MTC machine is represented in orange and the LTC one in blue.
- The third plot represents the temperature behaviour of the LT dispatchable load, both in the "base" scenario (blue) and in the "call" one (orange).
- The fourth plot represents the temperature behaviour of the LT dispatchable load, both in the "base" scenario (blue) and in the "call" one (orange).

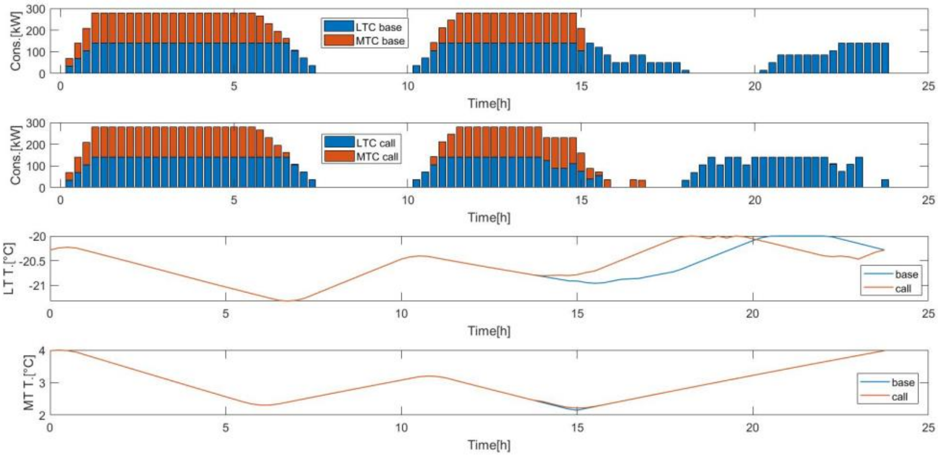

Figure 22: Autumn day, 50kW, UVAM "no call" case

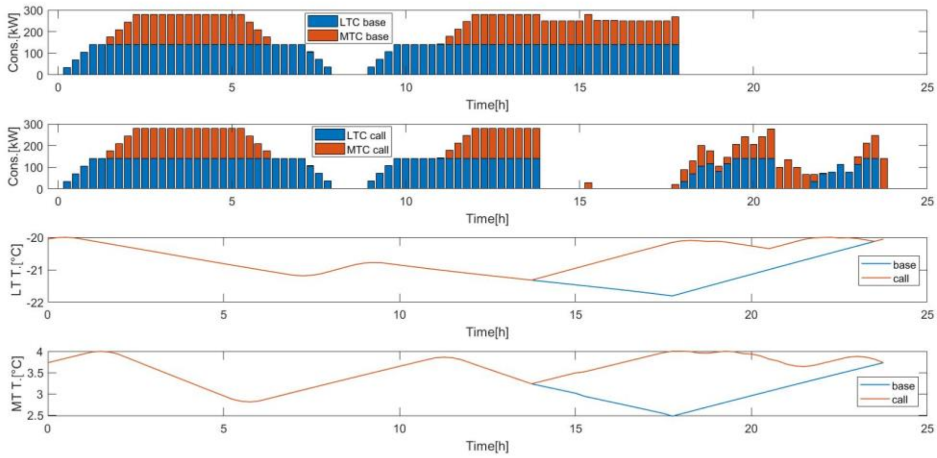

Figure 23: Autumn day, 250kW, UVAM "no call" case

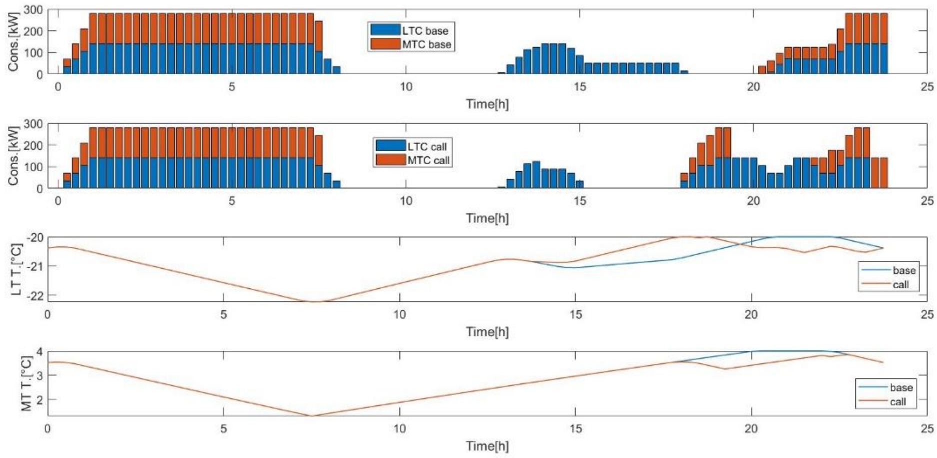

Figure 24: Winter day, 50kW, UVAM “no call” case

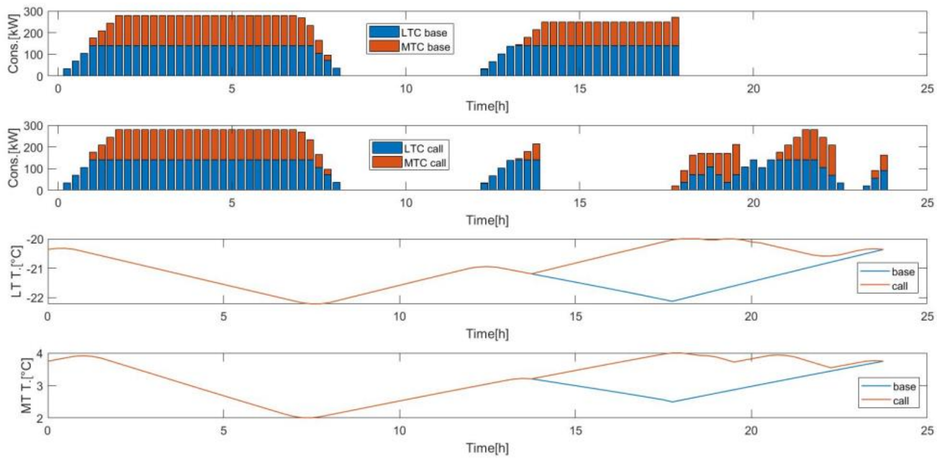

Figure 25: Winter day, 250kW, UVAM “no call” case

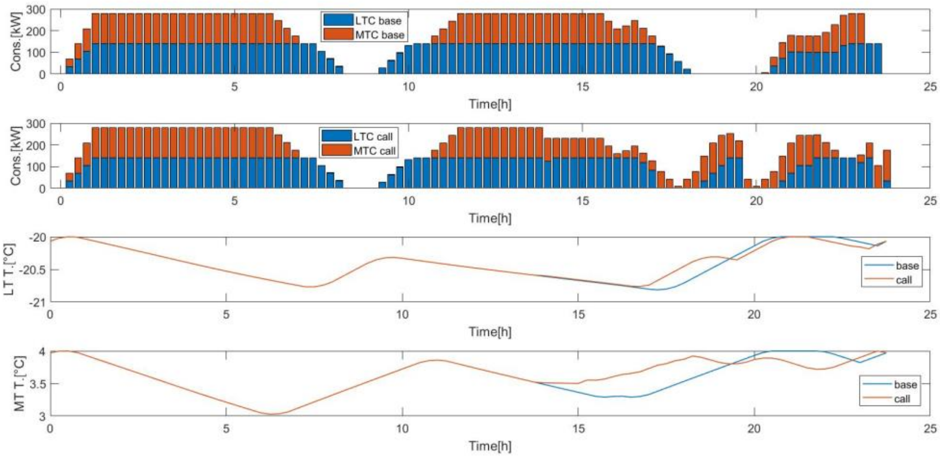

Figure 26: Summer day, 50kW, UVAM “no call” case

As previously mentioned, the summer typical day is the one characterised by the lowest cost increase for the “base” operating scenario. In fact, by comparing the first plot in figure 26 and the one in figure 20 (*no UVAM case*), they are almost equivalent.

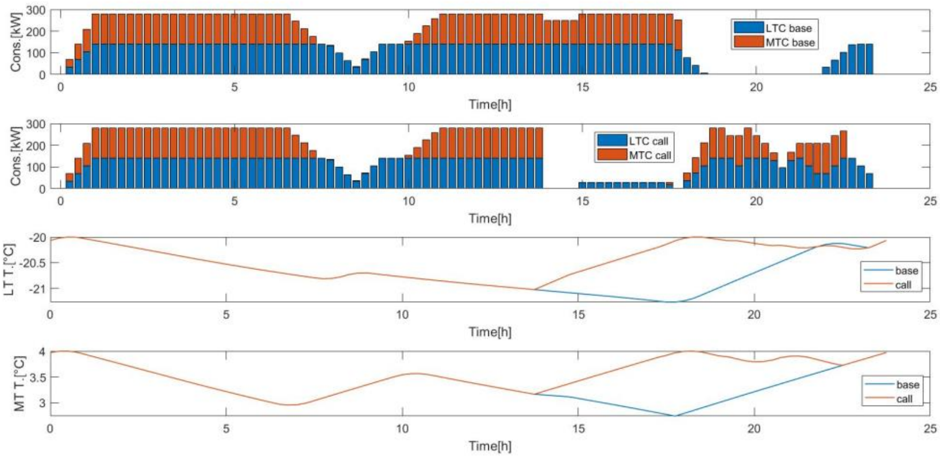

Figure 27: Summer day, 250kW, UVAM “no call” case

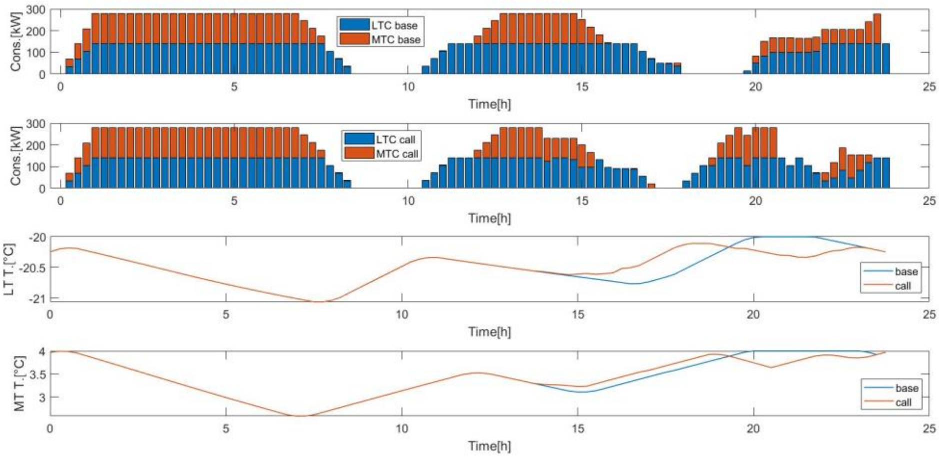

Figure 28: Spring day, 50kW, UVAM “no call” case

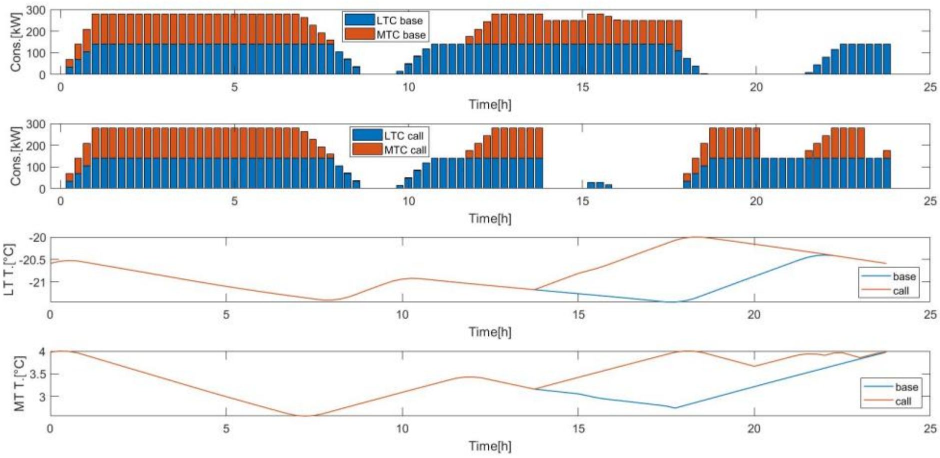

Figure 29: Spring day, 250kW, UVAM “no call” case

4.3 UVAM case

This case is further divided into two sub-analyses: the *UVAM’s architecture analysis* and the *“call” probability analysis* that are presented in the following sections.

4.3.1 UVAM’s architecture analysis

In order to perform this analysis a probability α_o equal to 5% is given to the “call” operating scenario in the objective function of the MILP model. This probability is chosen according to the UVAM pilot project results. In fact, as presented in chapter 2, the number of dispatching orders sent by Terna to the UVAMs during the year 2019, represented the 5% of the submitted offers.

The results, in terms of cost increase of the “base” and the “call” scenarios with respect to the *no UVAM case* are presented from Table 9 to Table 12. They are computed for all the five power modulations performed by the unit considered in the previous case.

1. Autumn typical day

Power modulation [kW]	Cost increase “base” [€/day]	Cost increase “call” [€/day]
50	0.074	1.83
100	0.39	3.33
125	0.72	4.24
200	2.71	5.97
250	3.802	8.05

Table 9: Autumn day, daily cost increase, UVAM’s architecture analysis

2. Winter typical day

Power modulation [kW]	Cost increase “base” [€/day]	Cost increase “call” [€/day]
50	0.45	0.94
100	1.43	2.16
125	1.75	2.75
200	3.93	4.44
250	6.57	6.49

Table 10: Winter day, daily cost increase, UVAM’s architecture analysis

3. Summer typical day

Power modulation [kW]	Cost increase “base” [€/day]	Cost increase “call” [€/day]
50	0.003	0.43
100	0.053	1.16
125	0.09	1.55
200	0.49	3.42
250	1.84	6.28

Table 11: Summer day, daily cost increase, UVAM’s architecture analysis

4. Spring typical day

Power modulation [kW]	Cost increase "base" [€/day]	Cost increase "call" [€/day]
50	0.098	0.68
100	0.26	1.59
125	0.78	1.77
200	2.29	3.52
250	4.96	6.75

Table 12: Spring day, daily cost increase, UVAM's architecture analysis

These results clearly show that in this case the "call" operating scenario is optimized since a 5% probability is given to it in the objective function of the MILP model. In fact, unlike the *UVAM "no call" case*, in this case the cost increase of the "call" scenario is much lower. Furthermore, it has the same trend of the "base" cost difference with respect to the power modulation performed by the unit. Oppositely, the "base" operating scenario results to be slightly more expensive since its weight in the objective function is lower in this case. As expected, by increasing the weight of the "call" operating scenario in the objective function, its operating costs decrease and, on the contrary, the costs of the "base" scenario increase. However, the impact of the statistical weight of the "call" scenario in the objective function will be analysed in the section 4.3.2.

The following figures show the supermarket's operation in terms of electrical input consumption and dispatchable loads' temperature. As done in the previous case, only the power modulations of 50 kW and 250 kW will be illustrated.

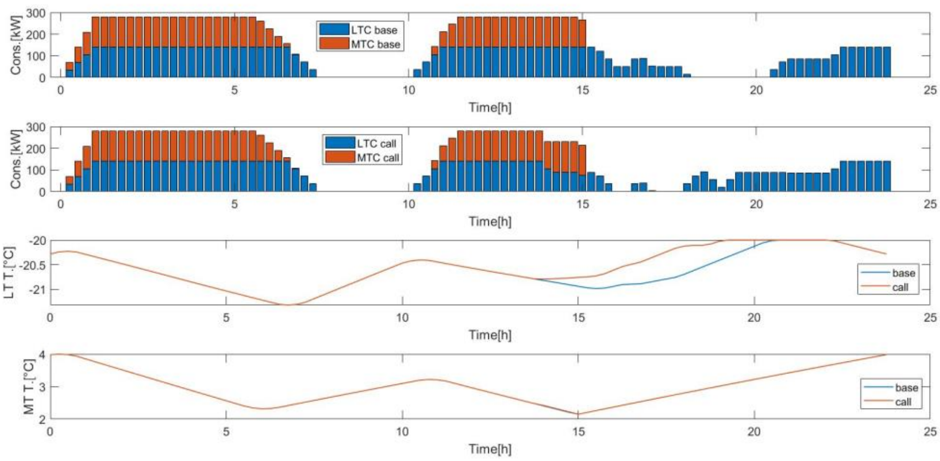

Figure 30: Autumn day, 50kW, UVAM's architecture analysis

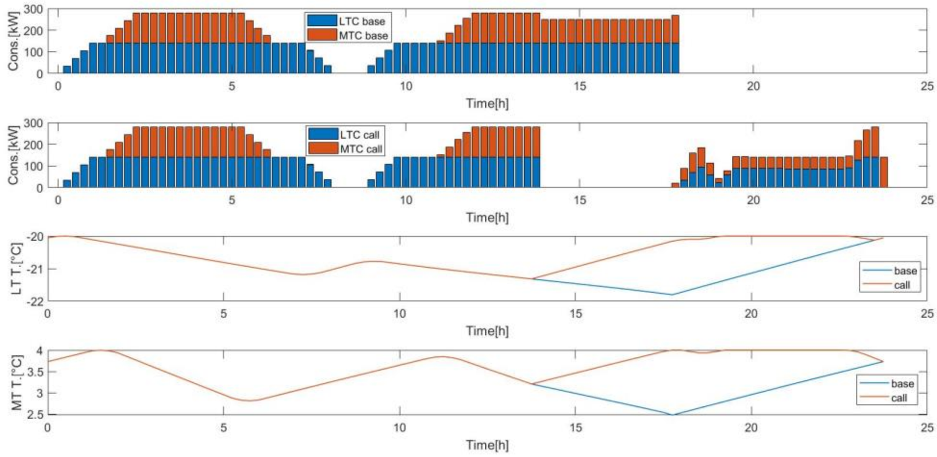

Figure 31: Autumn day, 250kW, UVAM's architecture analysis

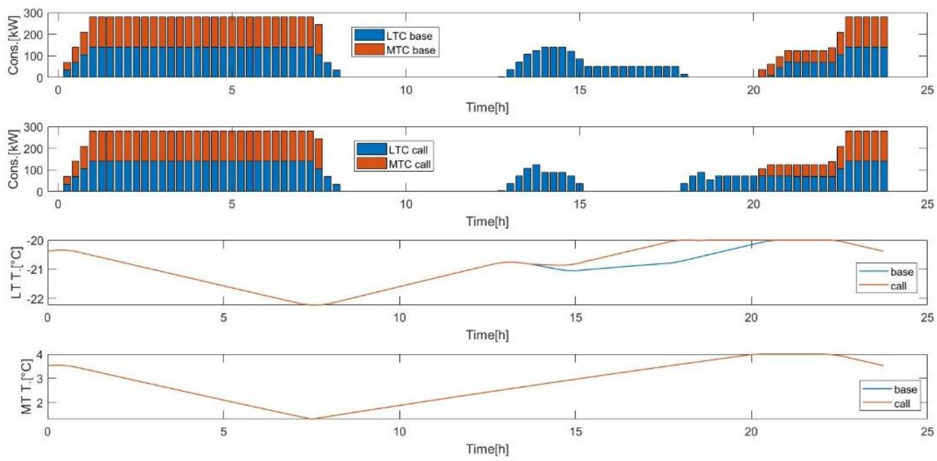

Figure 32: Winter day, 50kW, UVAM's architecture analysis

It is interesting to notice that, during the Winter season, only the LTC machine is used to perform the 50 kW power modulation to keep the operation as close as possible to the *no UVAM* one. In fact, as it is possible to notice from the MT temperature behaviour it does not change between the "base" and the "call" operating scenarios. The same trend is observed for power modulations of 100 kW and 125 kW. Instead, for high power modulations (200 kW and 250 kW) both machines must be mandatorily used to supply the service since, according to the machines' technical specifications, the maximum power modulation obtainable with a single machine is 140 kW.

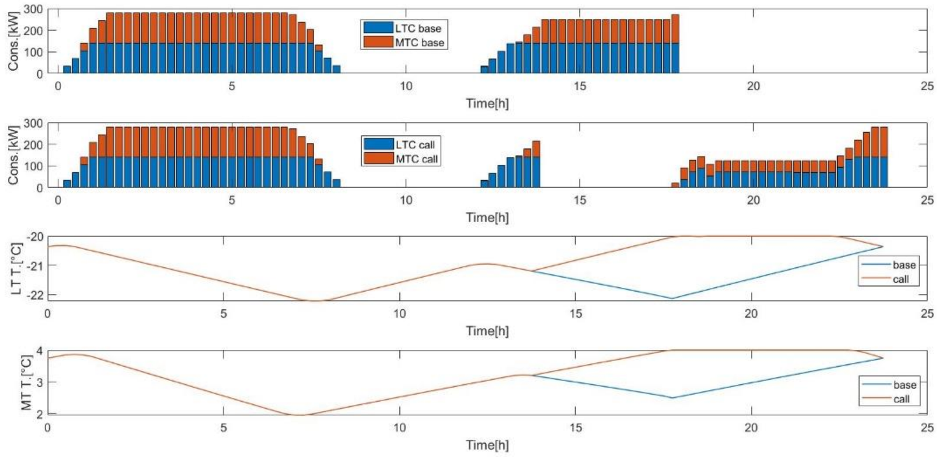

Figure33: Winter day, 250kW, UVAM’s architecture analysis

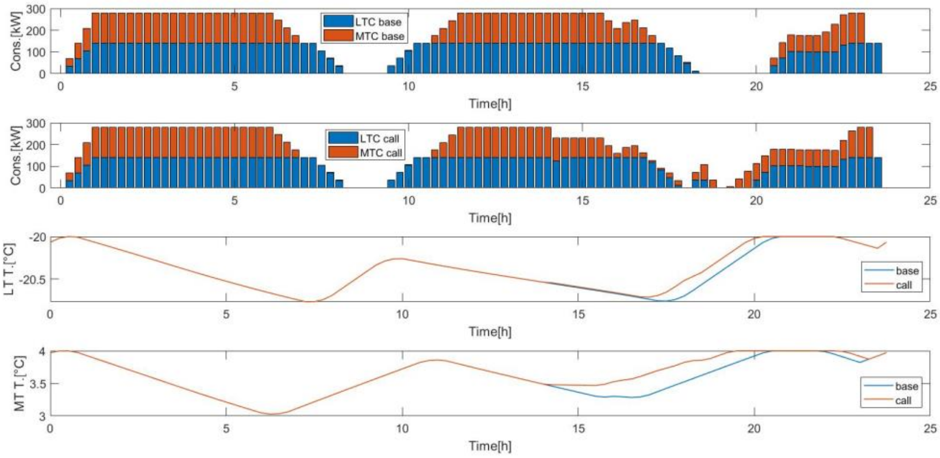

Figure34: Summer day, 50kW, UVAM’s architecture analysis

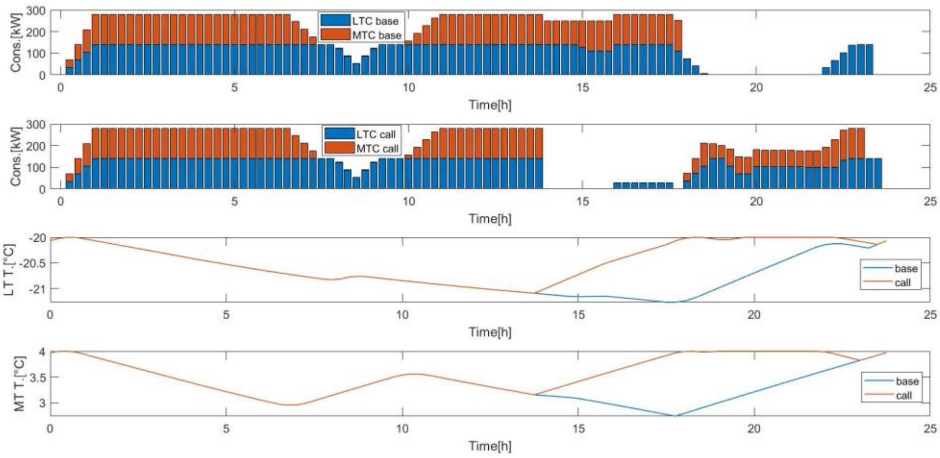

Figure35: Summer day, 250kW, UVAM’s architecture analysis

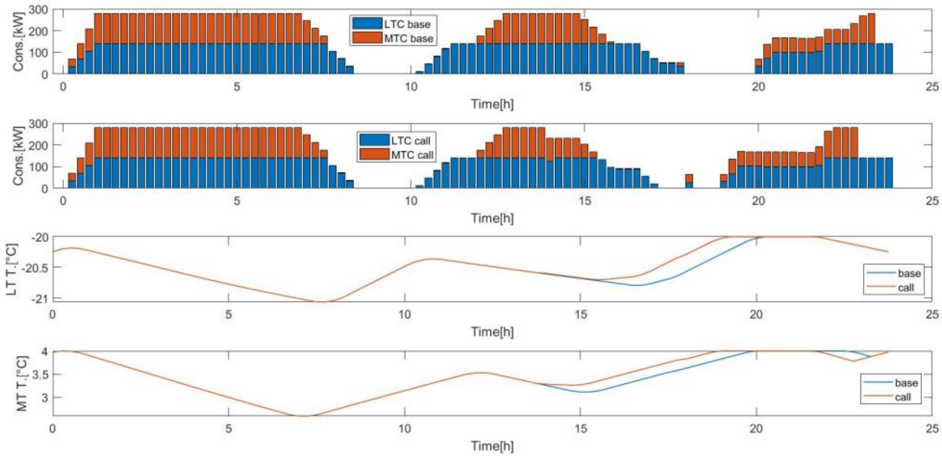

Figure36: Spring day, 50kW, UVAM's architecture analysis

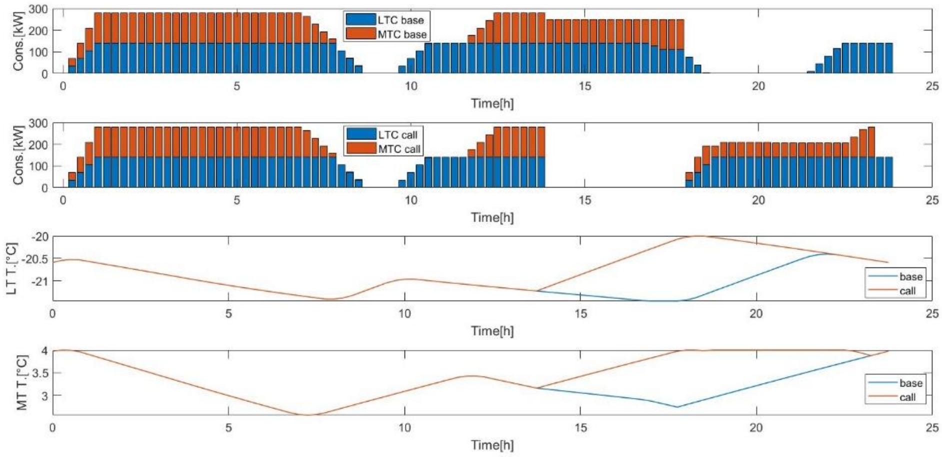

Figure37: Spring day, 250kW, UVAM's architecture analysis

After this brief presentation of the supermarket's operation, we will focus on the main objective of the present analysis that is to find the minimum number of supermarkets belonging to the UVAM that ensures the highest income. The structure of the analysis can be summarized in the following steps:

- The power modulation performed by the supermarket is set (i.e. the number of supermarkets belonging to the UVAM is set).
- It is assumed that during the weekends, the supermarket follows the *no UVAM case* operation since, according to the rules of the UVAM participation to the

forward ancillary services market, the aggregate cannot submit offers on Saturdays and Sundays.

- From Monday to Friday, the operation of the supermarket is represented by the "call" (or the "base") operating scenario if the dispatching order is (or is not) received from Terna.
- The annual cost increase (ΔC_{year}) due to the participation to the MSD is computed through equation (34) accounting for different frequencies of days in which the dispatching order is sent by the TSO.

$$\Delta C_{year} = \Delta C_{base} * n^o\ of\ \text{"base"}\ days + \Delta C_{call} * n^o\ of\ \text{"call"}\ days \tag{34}$$

- The annual fixed remuneration (a.f.r.) is computed with equation (35), it is independent from the acceptance of the offer by Terna. In the equation 0.6 represents the share of the revenues given to the supermarket's owner.

$$a.f.r. = \frac{30000 * 0.6}{number\ of\ units} \tag{35}$$

- The daily variable remuneration (d.v.r.), given to the aggregate only in case of correct execution of the dispatching order, is computed with equation (36).

$$d.v.r. = Price * service\ duration * \Delta p * 0.6 \tag{36}$$

- For every considered frequency of "call" days the annual variable remuneration (a.v.r.) is computed with equation (37).

$$a.v.r. = d.v.r. * n^o\ of\ \text{"call"}\ days \tag{37}$$

- Finally, for every considered frequency, the annual net revenues are computed as:

$$net\ revenues = a.v.r. + a.f.r. - \Delta C_{year} \tag{38}$$

Then, the analysis is iterated for all the considered power modulations performed by the unit (i.e. for all the considered number of supermarkets).

It is assumed that the number of “call” days is evenly distributed throughout the year, meaning that the number of “call” days is the same in every season. As mentioned at the beginning of the chapter, the price of the supplied service is 50 €/MWh and it is considered constant during the year as well as the dispatching order duration (4 hours).

The assumed frequencies of “call” days are: 0%, 5%, 10% and 20%, the last one represents a quite optimistic percentage compared to the pilot project results.

Since the annual revenues are computed accounting for different frequencies of the “call” days, this analysis has not been performed in the *UVAM “no call” case*. In such case the “call” operating scenario is not optimized leading to unusual, but expected, results as shown in figure 38.

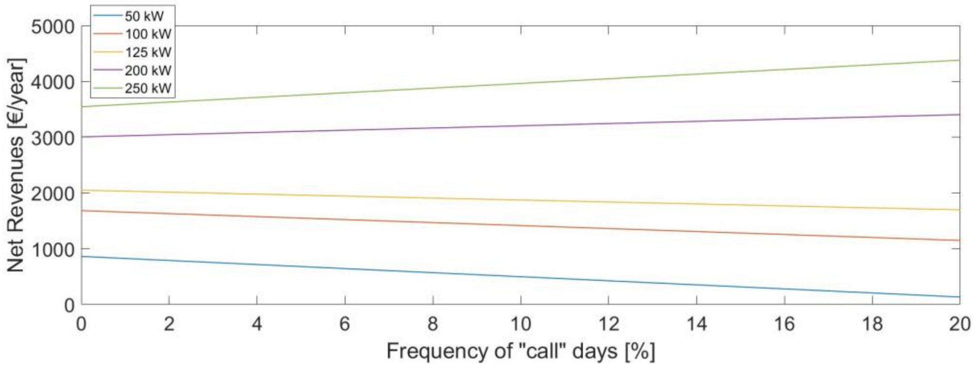

Figure 38: Annual revenues lines, UVAM “no call” case

The revenues lines resulting from the present analysis are illustrated in figure 39.

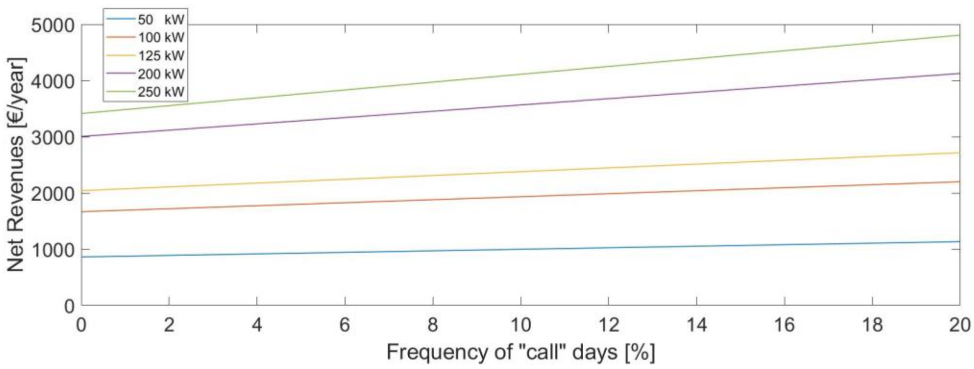

Figure 30: Annual revenues lines, UVAM’s architecture analysis

Figure 39 shows that when the "call" operating scenario costs are accounted in the objective function of the MILP model, the slope of the revenue lines become positive whatever the power offered is. This is because the optimized "call" scenario is characterised by low operating costs that are fully compensated by the remuneration derived from the service supply.

The figure above also shows that the UVAM's architecture that ensures the highest income is the one constituted by at least four supermarkets, offering a power modulation of 250 kW each. The results of this analysis are also presented, for every considered power modulation, from Table 13 to Table 17.

Frequency of "call" days [%]	DCost [€/year]	Fixed Remuneration [€/year]	Variable Remuneration [€/year]	Net Revenue [€/year]
0	39.13	900	0	860.87
5	47.50	900	76.5	928.99
10	55.87	900	153	997.13
20	72.60	900	306	1133.39

Table 13: Annual revenues, 50 kW, UVAM's architecture analysis

Frequency of "call" days [%]	DCost [€/year]	Fixed Remuneration [€/year]	Variable Remuneration [€/year]	Net Revenue [€/year]
0	134.25	1800	0	1665.75
5	153.85	1800	153	1799.14
10	173.46	1800	306	1932.54
20	212.67	1800	612	2199.33

Table 14: Annual revenues, 100 kW, UVAM's architecture analysis

Frequency of "call" days [%]	DCost [€/year]	Fixed Remuneration [€/year]	Variable Remuneration [€/year]	Net Revenue [€/year]
0	210.02	2250	0	2039.98
5	232.43	2250	191.25	2208.82
10	254.84	2250	382.5	2377.66
20	299.65	2250	765	2715.34

Table 15: Annual revenues, 125 kW, UVAM's architecture analysis

Frequency of "call" days [%]	DCost [€/year]	Fixed Remuneration [€/year]	Variable Remuneration [€/year]	Net Revenue [€/year]
0	595.77	3600	0	3004.24
5	621.33	3600	306	3284.67
10	646.89	3600	612	3565.1
20	698.04	3600	1224	4125.96

Table 16: Annual revenues, 200 kW, UVAM's architecture analysis

Frequency of "call" days [%]	DCost [€/year]	Fixed Remuneration [€/year]	Variable Remuneration [€/year]	Net Revenue [€/year]
0	1087	4500	0	3413
5	1120.59	4500	382.5	3761.91
10	1154.19	4500	765	4110.81
20	1221.38	4500	1530	4808.62

Table 17: Annual revenues, 250 kW, UVAM's architecture analysis

4.3.2 "call" probability analysis

The aim of this section is to perform an analysis on the sensitivity of the solution of the optimization to the statistical weight α_o given to the "call" operating scenario in the objective function of the MILP model.

The analysis is carried out by considering weights equal to 0% (*no UVAM case*), 5% (*UVAM's architecture analysis*), 10% and 20%. The only considered UVAM's architecture is the one that ensures the highest income, meaning that results are referred to a power modulation performed by the supermarket equal to 250 kW.

The daily cost increase of the "base" and "call" operating scenarios, for all the typical days, are reported in Tables 18 and 19. They are referred to probabilities of the "call" scenario in the objective function equal to 10% and 20% respectively.

Typical day	Cost increase “base” [€/day]	Cost increase “call” [€/day]
Autumn	3.802	8.05
Winter	6.57	6.37
Summer	1.86	6.19
Spring	4.97	6.75

Table 18: Typical days cost increase, “call” probability equal to 10%

Typical day	Cost increase “base” [€/day]	Cost increase “call” [€/day]
Autumn	3.802	8.05
Winter	6.57	6.37
Summer	1.94	5.58
Spring	5.03	6.63

Table 19: Typical days cost increase, “call” probability equal to 20%

The tables show that, by increasing the statistical weight of the “call” scenario in the objective function from 5% (*UVAM’s architecture analysis*) to 20% the operation during Winter and Autumn does not change. However, a variation in observed for the Summer and Spring typical days. In particular, by increasing the parameter α_o, the optimizer finds a cheaper “call” scenario operation and a slightly more expensive “base” operating scenario.

The similarity in the daily cost increase in the typical days, leads to a similarity in the obtainable annual revenues, as reported in Tables 20 and 21. These tables are referred to a statistical weight given to the “call” scenario in the objective function equal to 10% and 20% respectively.

Frequency of "call" days [%]	DCost [€/year]	Fixed Remuneration [€/year]	Variable Remuneration [€/year]	Net Revenue [€/year]
0	1088.36	4500	0	3411.64
5	1121.24	4500	382.5	3761.26
10	1154.12	4500	765	4110.88
20	1219.89	4500	1530	4810.11

Table 20: Annual revenues, "call" probability equal to 10%

Frequency of "call" days [%]	DCost [€/year]	Fixed Remuneration [€/year]	Variable Remuneration [€/year]	Net Revenue [€/year]
0	1097.32	4500	0	3402.69
5	1127.37	4500	382.5	3755.13
10	1157.42	4500	765	4107.58
20	1217.52	4500	1530	4812.48

Table 21: Annual revenues, "call" probability equal to 10%

In order to visualise the small difference in terms of annual revenues observed by increasing the weight of the "call" scenario from 5% to 20%, figure 40 shows the annual revenues lines computed by considering statistical weights α_o equal to 0%, 5%, 10% and 20%.

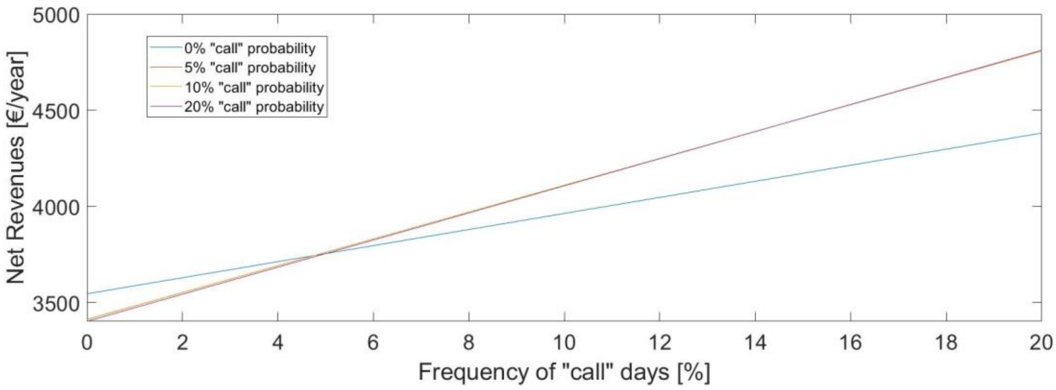

Figure 31: Annual revenues lines considering different statistical weights of the "call" scenario

The lines representative of the 5%, 10% and 20% "call" scenario probabilities are almost overlapped. Instead, a sensible difference is observed with respect to the 0% probability (*UVAM "no call" case*). The differences between these lines are just a matter of operating costs since the only considered modulating power is 250 kW, meaning that, given a frequency of “call” days, both the fixed and the variable remuneration are set. From figure 41 to figure 44 the operating costs of the “base” and the “call” scenarios are illustrated, for the four typical days, as a function of the probability α_o given to the “call” scenario in the objective function of the MILP model.

The figures show that even by increasing the statistical weight from 0% to 0.5% a sudden drop of the operating costs of the “call” scenario is observed. Subsequently, by further increasing the parameter α_o the cost curves become almost flat. Contrarily, a small increase of the operating cost of the “base” scenario is observed. However, this trend is only evident by switching from a null probability to a non-null one while, once a certain statistical weight is given to the “call” scenario, the trend becomes less relevant.

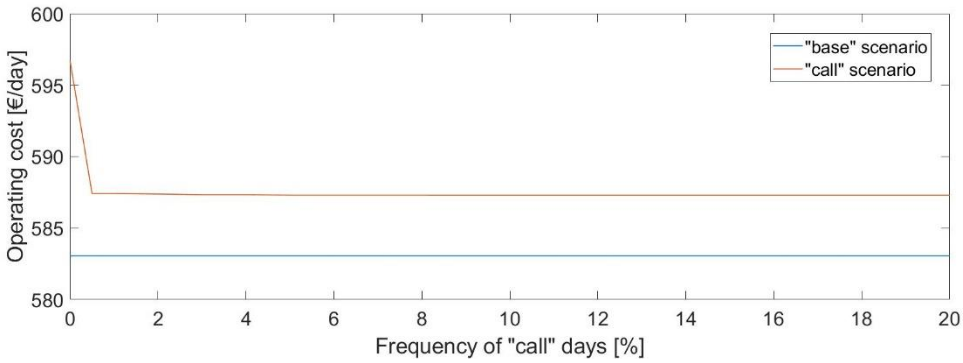

Figure 32: Autumn typical day operating costs curves considering different probabilities of the “call” scenario

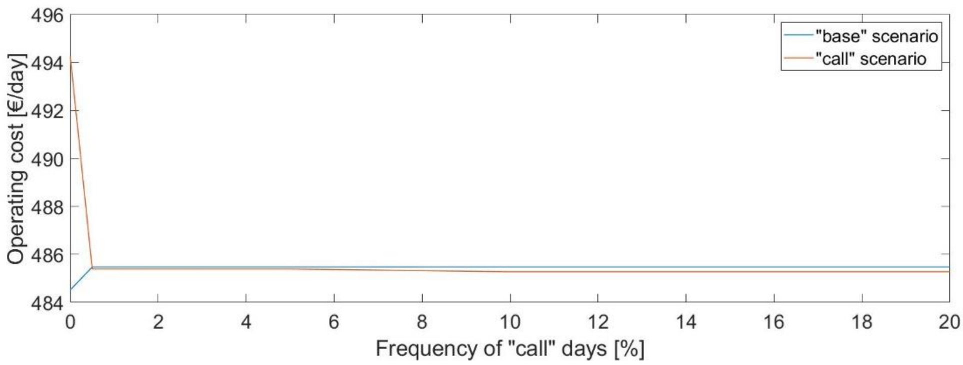

Figure 33: Winter typical day operating costs curves considering different probabilities of the “call” scenario

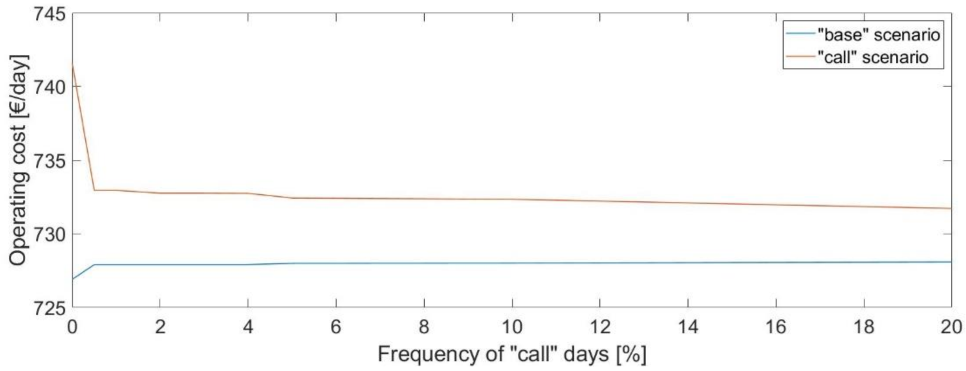

Figure 34: Summer typical day operating costs curves considering different probabilities of the “call” scenario

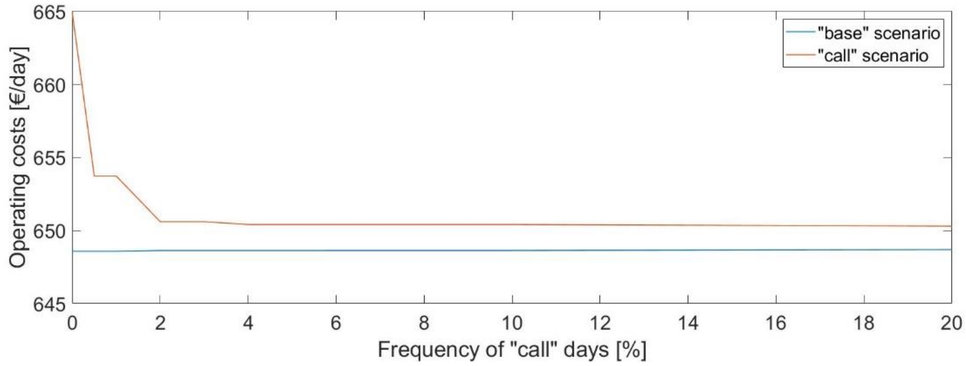

Figure 35: Spring typical day operating costs curves considering different probabilities of the “call” scenario

4.4 Conclusions

The UVAM’s best architecture is the one constituted by at least 4 supermarkets offering a power modulation of 250 kW. However, the supermarket’s participation to the MSD does not result to be particularly profitable since, by exploiting the flexibility obtained through an active management of the dispatchable thermal loads, the maximum annual income is 4812.48 €/year that does not represent a huge amount of money for a retail store. However, this result depends on many different factors, namely:

- Nowadays, UVAMs can only participate to the ancillary services market and must compete with the thermoelectric plants that are designed for supplying these kinds of services, making the obtainable profits very low. UVAMs might become more attractive in the future if the other energy markets will be opened to them or if a large penetration of renewable power plants will take place in the electric system causing a more difficult and expensive services supply for conventional plants.

- The profitability analysis is strongly dependent on the architecture of the UVAM, so it is difficult to draw general conclusions about UVAM's economic benefits. In this case a UVAM constituted by consumption units of the same type have been analysed, but the aggregate can be composed by very different kind of units to better exploit the synergies between different technologies.
- The only considered flexibility of the supermarket is the one obtained by the active management of the dispatchable thermal loads. However, it is possible to gain a degree of flexibility in the operation also exploiting the machines for the air conditioning. Instead of keeping the ambient temperature to a fixed value it is possible to let it change, always ensuring the thermal comfort conditions for the occupants of the store.

In order to obtain more general results about the potential that UVAMs can offer, it is needed to wait since up to now they are not yet fully integrated in the electric system, in fact Italy is in an experimental scenario in that sense. Moreover, a few data only regarding the supply of increasing balancing services are available to properly simulate a realistic operation of the UVAM as an effective resource for the ancillary services market. Finally, it is worth to highlight that the current legislation of the electric dispatching has been laid down without considering the presence of these resources. However, it is currently changing to encourage the adoption of innovative ways for the electric grid management in order to reach the goals foreseen in ten years. There is no doubt that the presence of alternative resources able to provide grid services will be needed in the near future and UVAMs represent for sure an interesting option.

4.5 Further developments

The UVAM work frame is a very recent field of study and there are still a lot of paths to explore. In particular, several different UVAM architectures involving the consumption unit considered in this work can be studied:

- Without changing the main focus of this work, it is possible to involve in the UVAM different consumption units. For example, residential units that offer flexibility to the aggregate through the management of smart devices such as dish washers or washing machines.

- The supermarket presented in this work can be coupled with production units such as a PV plant that allows to gain flexibility through the management of storage units in order to create a real "mixed" aggregate.
- Consumption units cannot only supply grid services through their participation to the ancillary services market. Therefore, it could be interesting to compare the results obtained in this work and the ones obtained by studying the supermarket participation to alternative grid services such as the Capacity Market or the interruptibility service. They may result to be more attractive from an economic point of view for this kind of unit.

References

[1]. Ministero dello Sviluppo Economico, Ministero dell'Ambiente e della Tutela del Territorio e del Mare, Ministero delle Infrastrutture e dei Trasporti. Piano Nazionale Integrato per l'Energia e il Clima, 2019.

[2]. Politecnico di Milano. Renewable Energy Report. *Gli scenari futuri delle rinnovabili in Italia*, 2019.

[3]. https://www.terna.it/it/sistema-elettrico/dispacciamento/dati-esercizio.

[4]. GME. Relazione Annuale 2019.

[5]. ARERA. Testo Integrato del Dispacciamento Elettrico (TIDE), Orientamenti Complessivi. Documento per la consultazione 322/20197R/eel, 2019.

[6]. REGOLAMENTO (UE) 2015/1222 DELLA COMMISSIONE che stabilisce orientamenti in materia di allocazione della capacità e di gestione della congestione. *Gazzetta ufficiale dell'Unione europea*, 2015.

[7]. REGOLAMENTO (UE) 2017/2195 DELLA COMMISSIONE che stabilisce orientamenti in materia di bilanciamento del sistema elettrico. *Gazzetta ufficiale dell'Unione europea,* 2017.

[8]. ARERA. Prima apertura del mercato per il servizio del dispacciamento (MSD) alla domanda elettrica ed alle unità di produzione anche da fonti rinnovabili non già abilitate nonché ai sistemi di accumulo. Istituzione di progetti pilota in vista della costituzione del testo integrato dispacciamento elettrico (TIDE) coerente con il *Balancing Code* europeo, 2017.

[9]. Terna S.p.A. Regolamento recante le modalità per la creazione, qualificazione e gestione di unità virtuali di consumo abilitate al mercato dei servizi di dispacciamento-regolamento MSD, 2017.

[10]. Terna S.p.A. Procedura e regole per l'approvvigionamento a termine di risorse di dispacciamento per i soggetti titolari di unità virtuali di consumo abilitate al mercato dei servizi di dispacciamento per il periodo 19 giugno-30 settembre 2017, 2017.

[11]. Terna S.p.A. Regolamento recante le modalità per la creazione, qualificazione e gestione di unità virtuali di produzione abilitate al mercato dei servizi di dispacciamento-regolamento MSD, 2017.

[12]. ARERA. Approvazione del regolamento, predisposto da Terna S.p.A. ai sensi della deliberazione dell'Autorità 300/2017/R/eel, relativo al progetto pilota per la partecipazione di unità virtuali miste al mercato per il servizio di dispacciamento (MSD). Adeguamento della deliberazione dell'Autorità 300/2017/E/eel, 2018.

[13]. Terna S.p.A. Regolamento recante le modalità per la creazione, qualificazione e gestione di unità virtuali abilitate miste (UVAM) al mercato dei servizi di dispacciamento-regolamento MSD UVAM, 2018.

[14]. Terna S.p.A. Procedura per l'approvvigionamento a termine di risorse di dispacciamento per i soggetti titolari di unità virtuali abilitate miste (UVAM) al mercato dei servizi di dispacciamento, 2018.

[15]. Terna S.p.A. Grid Code – Chapter 4 – Dispatching regulations.

[16]. Terna S.p.A. Procedura per la selezione delle risorse per la fase di programmazione del MSD.

[17]. Terna S.p.A. Procedura per la selezione delle risorse per il mercato di bilanciamento.

[18]. Terna S.p.A. Grid Code – Chapter 7 – Regulation of financial charges for the dispatching service and transmission service.

[19]. Politecnico di Milano. Electricity Market Report. *L'apertura del MSD oltre i progetti pilota: quali ricadute per il sistema paese?*, 2019.

[20]. Enel X. ENEL X launches first project in Italy to aggregate residential storage units offering network balancing services, 2020.

[21]. Andrea Bassi. A MILP optimization model for the impact assessment of dispatchable thermal loads in retail industry. *Tesi di Laurea Specialistica in Ingegneria Energetica – Politecnico di Milano*, 2018-2019.

[22]. Paolo Barbato, Carlo Alberto Gaetaniello. A novel MILP decomposition algorithm ensuring global optimality for the predictive design of complex Multi-Energy Systems. *Tesi di Laurea Specialistica in Ingegneria Energetica – Politecnico di Milano*, 2018-2019.

[23]. Francesco Castellani. Distributed Energy Resources: a new asset for ancillary services market. *Tesi di Laurea Specialistica in Ingegneria Energetica – Politecnico di Milano*, 2017-2018.